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Apparatus for dynamic interface testing between reinforcing inclusions and sand

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Apparatus for Dynamic Interface Testing between Reinforcing Inclusions and Sand

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TABLE OF CONTENTS

TITLE PAGE i

CERTIFICATE OF APPROVAL ii

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF FIGURES viii

ABSTRACT 1

CHAPTER 1 3

1 INTRODUCTION 3

1.1 CONSTRUCTION APPLICATIONS 4

1.2 INTERACTION 5

1.3 STATIC LOADING VERSUS DYNAMIC LOADING 6

1.4 FACTORS INFLUENCING LABORATORY TEST RESULTS 7

1.5 BOUNDARY CONDITIONS 8

1.6 THREE CATAGORIES OF LABORATORY METHODS 9

1.6.1 EQUIVALENT HOMOGENIZATION METHODS 10

1.6.2 EXPLICIT MODELING METHODS 10

1.6.3 LIMIT EQUILIBRIUM METHODS 11

1.6.4 PULLOUT DIRECT SHEAR TESTS 11

1.7 PULLOUT SHEAR BOX TEST 11

1.8 THESIS OBJECTIVE 12

1.9 CHAPTER SUMMARY.. 13

CHAPTER 2... 18

2 LITERATURE REVIEW.. 18

2.1 SHEAR LAG ANALYSIS OF PLANAR REINFORCMENTS. 18

2.2 PULLOUT TESTS TO INVESTIGATE LOAD TRANSFER... 21

2.3 DYNAMIC INTERFACE SHEAR STRENGTH OF GEOSYNTHETICS.. 24

2.4 SUMMARY OF LITERATURE REVIEW........................ 26

CHAPTER 3... 32

3. EQUIPMENT AND PROCEDURE.................................. 32

3.1 GENERAL REQUIREMENTS.................................... 33

3.2 MATERIALS.. 35

3.2.1 ALUMINUM.. 36

3.2.2 BUTYL RUBBER.. 37

3.2.3 CLEAR POLYCARBON..................................... 38

3.2.4 ACRYLIC... 38

3.2.5 UNTREATED GLASS... 39

3.2.6 POLYTETRAFLUOROETHYLENE 39

3.2.7 POLYVINYL CHLORIDE.................................... 39

3.3 FABRICATED EQUIPMENT.................................... 40

3.3.1 PULLOUT SHEAR BOX...................................... 40

3.3.2 REINFORCING INCLUSIONS.......................... 42

3.3.3 SHAKE TABLE MOUNTING BASE FRAME......... 43

3.3.4 PRESSURE BAGS.. 44

3.3.5 COMPOSIT WINDOW.................................... 46

3.3.6 PULLOUT SHEAR BOX SPACER..................... 46

3.3.7 FRICTION LINERS.. 47

3.4 PURCHASED AND ACQUIRED EQUIPMENT.................. 47

3.4.1 AIR PRESSURE SYSTEM.................................. 47

3.4.2 PULLOUT ASSEMBLY AND MOTOR................ 48

3.4.3 DATA ACQUISITION...................................... 48

3.4.4 SHAKING TABLE... 48

3.5 ELECTRICAL REQUIREMENTS................................. 49

3.6 PROCEDURE.. 49

3.7 SUMMARY OF EQUIPMENT AND TEST PROCEDURES... 51

CHAPTER 4.. 59

4 EQUIPMENT ASSEMBLY AND RESULTS FROM ALL OF THE TESTS.. 59

4.1 TEST EQUIPMENT FABRICATION AND ASSEMBLY....... 59

4.1.1 TOLERANCES.. 60

4.1.2 CONSTRUCTION PROCESS.............................. 61

4.2 PERFORMANCE TEST RESULTS................................ 63

4.3 FULL-SCALE INTERFACE TEST RESULTS.................. 65

4.4 SUMMARY OF EQUIPMENT FABRICATION AND TEST RESULTS 66

CHAPTER 5 70

5 RESEARCH SUMMARIES AND FINAL REMARKS 70

5.1 EQUIPMENT SUMMARIES 70

5.2 TEST SUMMARIES 71

5.3 RESEARCH SUMMARY 72

5.4 RESEARCH CONCLUSIONS 73

5.5 FUTURE RECOMMENDATIONS 75

REFERENCES 76

VITA 79

LIST OF FIGURES

CHAPTER 1

1-1	HIGHWAY ENGINEERING APPLICATIONS	14
1-2	REINFORCED SOIL FAILURE ZONE	14
1-3	TYPICAL LANDFILL LINER SYSTEM	15
1-4	SOLID WASTE ACTING ON LINER SYSTEM	15
1-5	SAND-INCLUSION INTERFACE......................................	16
1-6	DYNAMIC INTERFACE TEST APPARATUS........................	17

CHAPTER 2

2-1	AUTOMATED PLANE-STRAIN REINFORCEMENT CELL.......	28
2-2	LARGE SCALE PULLOUT BOX AND REACTION FRAME......	29
2-3	SHAKING TABLE FACILITY..	30
2-4	GEOSYNTHETIC TO GEOMEMBRANE FORCE DIAGRAM....	30
2-5	GEOTEXTILE TO GEOMEMBRANE FORCE SLIP MODEL......	31
2-6	STIFFNESS AND DAMPING PARAMETERS......................	31

CHAPTER 3

3-1	DYNAMIC INTERFACE TEST APPARATUS........................	52
3-2	CONVENTIONAL PULLOUT BOXES & THE PULLOUT SHEAR BOX..	53
3-3	INTERNAL COMPONENTS OF THE PULLOUT-SHEAR BOX ...	54

3-4 SIDE VIEW OF THE PULLOUT-SHEAR BOX 55

3-5 CLOSED END VIEW OF THE PULLOUT-SHEAR BOX 56

3-6 VALVE STEM HOLE.. 56

3-7 AIR BAG FRAME... 57

3-8 COMPOSITE WINDOW AND PULLOUT SHEAR BOX SPACER.. 57

3-9 AIR PRESSURE SYSTEM.. 58

CHAPTER 4

4-1 PROTOTYPE.. 68

4-2 DYNAMIC INTERFACE TESTING APPARATUS.................. 69

ABSTRACT

Many earth systems require embedded inclusions to reinforce the soil. Geotechnical engineers often measure the shear resistance provided by the reinforcement under static conditions. However, many systems are subject to dynamic loads. Equipment is commonly available to provide information on load transfer mechanisms under static conditions between reinforcing inclusions and soil. The load transfer is complex and depends on many variables such as inclusion geometry, stiffness, and texture, as well as soil consolidation stress, density, and internal friction angle. To assess the relative importance of these parameters, the variables have to be isolated by the test apparatus. The test apparatus must also be able to impose appropriate boundary conditions. In order to study interface behavior under dynamic conditions, a well-designed testing device is required.

The goal of this project was to develop a laboratory device capable of isolating pertinent test variables to allow the study of the behavior of reinforcing inclusions embedded in sand under static and dynamic conditions. Several performance tests were conducted to evaluate the functionality of individual components of the dynamic interface-testing device. Some of the components initially failed and modifications had to be made in either the design or fabrication process. After passing all performance tests, the components were assembled to complete the dynamic interface test apparatus. Two full-scale interface tests, one-static and one-dynamic, were conducted to ensure that the dynamic interface test apparatus functioned as designed. The full-scale tests were

performed under identical conditions except that the dynamic test vibrates the pullout shear box horizontally at a rate of 5 cycles per second with an amplitude of 0.05 inches.

The test results indicate that all of the components meet strength and functionality criteria. Additionally, the new apparatus allows for visual observation of the interaction between the inclusion and the soil. The dynamic interface test apparatus will allow the behavior between reinforcing inclusions and sand to be studied under both static and dynamic loading conditions.

CHAPTER 1

1 INTRODUCTION.

Geotechinical engineers are concerned with understanding the pullout behavior between soil and reinforcing inclusions. Understanding this interaction is essential to the design of reinforced soil structures. Reinforcements enhance the performance of many earth systems. Reinforcing inclusions are typically made from metal or plastic materials. Understanding the soil-inclusion interaction may also benefit the manufacturing of reinforcing inclusions by optimizing the inclusion material and geometry. Poor understanding of the behavior usually results in overly designed systems that are not cost effective. Most engineers often compensate for the lack of knowledge on performance by including higher factors of safety.

Economic loss resulting from uncertainty in the soil-reinforcement behavior may be curtailed by research directed at understanding this reciprocal activity. The knowledge gained from research will ultimately improve design methods. Currently, analysis of interface tests falls in three fundamental categories: Equivalent Homogenization Methods, Explicit Modeling Methods, and Limit Equilibrium Methods. Each of these methods allows the interface behavior between reinforcing inclusions and the soil at either the microscopic or the macroscopic level to be described. By evaluating the combined responses at each level, the net behavior of the reinforced soil system may be understood using a process similar to superposition.

1.1 CONSTRUCTION APPLICATIONS.

Embedded inclusions have many construction applications. Highway engineers, foundation specialists, and landfill designers routinely reinforce soil with stiff inclusions for a variety of purposes. For example, a highway project may require a retaining wall along a hillside cut adjacent to a roadway. Figure 1-1 illustrates a common hillside cut that incorporates reinforcing inclusions embedded into the surrounding soil. The engineer is concerned with the gross lateral resistance provided by the anchored inclusion to ensure that the wall does not become unstable. Figure 1-2 depicts a simplistic pressure diagram and typical failure surface for a reinforced hillside cut. In another example, a foundation specialist may have to stabilize foundations placed on weak soil. The engineer is concerned with the ability of reinforcing materials to reduce the potential for shear failure within the underlying soil. By controlling the shear zones, the bearing capacity of the undesirable soils is increased. Finally, landfills typically require lining the bottom and sides with impermeable geomembranes. The liner reduces the risk of contaminants permeating through the soil and leaking into the subsurface environment. Figure 1-3 shows a typical landfill liner system. The forces generated by the refuse on the liners may create side slope instability with the waste causing the liner to pull out of the shallow anchor trench. Figure 1-4 shows a typical anchor trench system commonly employed. The liner may tear or puncture after it is pulled out, which would allow contaminants to migrate into any unprotected ground or aquifer systems.

1.2 INTERACTION.

The manner in which the loads propagate through the soil mass is also of concern for geotechnical engineers since soils are typically stronger in compression than shear. By embedding reinforcing inclusions within the soil matrix, significant increases in shear strength may be realized to stabilize the soil system. Since the inclusions are much stiffer than the soil, the soil initiates shearing and then transfers excess shear stresses to the inclusion, thereby reinforcing the soil. This transfer process takes place in the vicinity of the common boundary or surface between the soil and the reinforcing inclusion. Figure 1-5 illustrates an interface or surface regarded as the common boundary between the soil and the reinforcing inclusion.

The interaction along the interface can be described as reciprocal actions or influences regarding the physical properties of the soil, such as internal friction angle, density, grain size and shape, and consolidation pressure, as well as the properties of the inclusion such as geometry, stiffness, material, and texture. Hence, the performance of the inclusion influences the action of the soil. The influence of each parameter must be clearly understood to produce more cost-efficient designs. Furthermore, reinforcements reduce volumetric strains as well as induce large shear strains. When the soil is reinforced and then undergoes shear strain, dilation is reduced. Lateral deformations within the soil are also reduced. Finally, the shear resistance is transferred to the reinforcing inclusion by means of friction along the planar surface as well as by passive soil resistance. Passive soil resistance depends on such factors as height and spacing of ribs on the inclusion as well as soil density, particle size and shape. The relative importance of all these parameters must be understood to understand the mechanical interaction between the sand and the reinforcing inclusion.

1.3 STATIC LOADING VERSUS DYNAMIC LOADING.

The loads applied to the earth system can be either static or dynamic in nature. Static loads, induced through the ground, result from dead weights, affixed forces, and lateral earth pressures. Dynamic loads due to earthquakes, traffic, machinery, wind, waves, construction operations, mining, and explosions actively impart vibrations. Geotechnical engineers are interested in applying test results that model the anticipated field environment for their design. Therefore, experimental studies that can reproduce appropriate static and dynamic behavior is essential. There is a moderate amount of information available regarding the static interaction between embedded inclusions and soil. Recent studies have examined the experimental pullout behavior from load transfer tests conducted on compressed soil and reinforcing inclusions (Abramento and Whittle, 1995) and from monotonic and cyclic pullout response of geogrids (Fannin and Raju, 1993; Raju and Fannin, 1997). However, the availability of dynamic interface performance tests is extremely limited. The most recent dynamic tests focused on the interface behavior between two geosynthetics (Yegian and Lehlaf, 1992; Yegian et. al, 1998).

Stress-strain behavior under dynamic loads is fundamentally different from that developed under static loads. In addition, dynamic effects, such as inertia and resonance, complicate the behavior. Dynamic loads are also imparted at different frequencies. For instance, earthquakes typically produce loads at much lower frequencies than machine vibrations that result from unbalanced forces. The typical frequency range of earthquakes is 2–10 Hz. In contrast, machines (such as diesel engines) may operate at 3000 revolutions per minute and produce frequencies as high as 50 cycles per second. The frequency of excitation has a significant effect on the response of the system, especially if the excitation frequency is close to the resonant frequency of the system. The resonant condition depends on the mass, stiffness, and damping for the system (Biggs, 1964; Das, 1993; Whitman and Dobry, 1985). This study addresses only dynamic effects relevant to geotechnical interface testing between sand and reinforcing inclusion.

1.4 FACTORS INFLUENCING LABORATORY TEST RESULTS.

The soil type, inclusion, test apparatus, and the pullout action all influence laboratory interface test results. Soil parameters that affect behavior include particle size, grain-size distribution, relative density, and effective confining stress. Soils with larger particle sizes develop larger zones of shear failure, which creates greater mobilized inertia. The increased inertia contributes to the formation of a larger passive plug producing greater bearing capacity and more resistance to accelerations. Shear strength characteristics of the soil refer to whether the soil develops shear resistance due to friction, cohesion, or by some friction-cohesion combination. The focus of this study will be granular soil developing shear resistance by way of friction. The effective confining stress may have a major influence on the results. If the confining stress is not applied uniformly, pressure bulbs develop. These bulbs produce localized anisotropic pressure conditions, unaccountable internal test stresses, and also contributes to the formation of shear planes.

When the shear planes become continuously distributed penetrating throughout the soil mass, shear failure results. Inclusion test specimens influence the interactive behavior as a result of the effects of material tensile strength, stiffness, and geometry. The relative stiffness between the soil and reinforcement determines whether the inclusion will behave as an extensible or rigid material. Extensible materials take up increments of stress as the material stretches; whereas, rigid materials mobilize peak stress with insignificant strain. Recognizably, the stages of stress mobilization for extensible materials are different than those stages brought about by rigid materials. Experimental apparatuses ultimately determine the scale of the test by regulating the dimensions of the specimens that can be tested. The test apparatus also imposes all of the boundary conditions. The applied pullout action can be either at a constant rate of displacement or a constant rate of loading.

1.5 BOUNDARY CONDITIONS.

There were several fundamental concerns that were identified in the early stages of development for the pullout box related to the imposed boundary conditions. First, it is essential that the stresses be imposed uniformly on the soil sample. Uniformly imposed stresses will also allow for a more simplified analysis of the experimental test results. Ensuring that the planar area of the embedded inclusion remains the same while the inclusion is pulled out of the box also simplifies the analysis. Two slots in the pullout box allow the reinforcement to be pulled out of the box as well as minimize the amount of soil escaping through the slot as the pullout process unfolds. The required clear distance separating the outside edge of the embedded reinforcing inclusion and the inside wall of the pullout box is a function of the soil grain size. The size of the grains has a direct influence on the width of the pullout resistance band that builds up between the edge of the embedded inclusion and the sidewall of the pullout box. The geometry of the pullout box effects the test scale and ultimately the validity of the test. These two issues depend on the aspect volume ratio of soil to reinforcement (Fannin, 1997; Larson, 1992). If the volume of reinforcement is large, as in the case of a small test apparatus, the results may not be applicable or reliable for use in actual construction applications.

1.6 THREE CATAGORIES OF LABORATORY METHODS.

There are three categories of laboratory test analysis that are used to describe the mechanical interaction between the soil and the embedded inclusion:

1. Equivalent Homogenization Methods (EHM).
2. Explicit Modeling Methods (EMM).
3. Limit Equilibrium Methods (LEM).

Each of the three methods takes a unique approach to understanding the interface behavior between soil and reinforcing inclusions. Combined, the methods describe the total response at the macroscopic level and provide understanding of the microscopic behavior. For example, a hillside cut slope that is reinforced with several inclusions may be analyzed using EHM. The resistance provided by an inclusion embedded into the soil can be determined using LEM. Once the characteristics of either the soil or the inclusion change, a new test has to be performed. Finally, EMM may be used to determine the individual effects of variables on load transfer mechanisms and strain processes.

1.6.1 EQUIVALENT HOMOGENIZATION METHODS.

The EHM model assumes that the behavior of the stiffer inclusion may be modeled within the soil matrix as periodically spaced, very firm, elastic, thin layers. The combined response of the soil and reinforcing inclusions is analyzed at the macroscopic level; and the behavior is based on rules of mixtures for elastic properties of composites. For these types of experiments, comparison of the boundary measurements for different volume fractions, spacings, and types of reinforcements are used to evaluate the composite properties. The common laboratory methods include the triaxial tests, plane strain tests, direct shear inclusion tests, and direst simple shear tests.

1.6.2 EXPLICIT MODELING METHODS.

Explicit modeling methods provide qualitative observations for the mechanisms of interaction between the soil and the reinforcing inclusion. EMM uses shear lag analysis or non-linear algebra to relate material properties, geometry, interface friction angle, and external consolidation stress to the pullout response, tensile stress, and the distribution of surface tractions. Tensile stresses in the reinforcement and deformation properties in the reinforced soil matrix provide quantitative evaluations for the composite elements. Integrating the elastic strains occurring within the inclusion describes the pullout response. These tests require data acquisition systems because of the large amount of instrumentation. Some of the tests include plane strain tests, direct shear box inclusion tests, and the automated plane strain reinforcement (APSR) cell tests.

1.6.3 LIMIT EQUILIBRIUM METHODS.

Simplified models are used to evaluate the stability of reinforced soil assuming that uniform shear resistance is maintained along the soil-reinforcement interface and tensile stresses are generated in the reinforcement. The forces generated at corresponding displacements are recorded. Stress-strain curves are plotted and friction angles are then computed. The tests commonly used with limit equilibrium methods are the reinforced direct shear box tests, direct simple shear tests, and pullout tests (Larson, 1992).

1.6.4 PULLOUT DIRECT SHEAR TESTS.

The direct shear box can be used to directly measure the interface friction angle between sands and various construction materials by replacing the lower half of the standard shear box with some solid material. However, the solid must be planar because the test imposes large shear deformations within a relatively small volume of soil. Pullout tests resemble direct shear tests except that the soil is stagnant on both sides of the withdrawn reinforcing inclusion instead of only the bottom side of the inclusion. Pullout tests, also known as anchorage tests, indirectly measure a combination of resistance resulting from skin friction and passive resistance. The stress state mobilized during these tests is very complex and requires further research. Koerner (1998) describes the pullout test as being one of the most sophisticated and expensive of all geosynthetic performance tests.

1.7 PULLOUT SHEAR BOX TEST.

Test results that are both consistent and repeatable help to validate performances from new experimental test configurations. Ideally, results from tests performed with a new test apparatus should be compared with the results from similar tests published in the literature to determine the amount of scatter in the data under similar test conditions. However, precise comparisons may not be possible because many researchers attempt to improve existing interface testing methods. These improvements modify various test boundary conditions. Boundary conditions affect all test results including the results from soil-reinforcement interaction tests. Presently, there are no standard laboratory scales which accurately represent in-situ conditions. The test scale determines the degree to which the laboratory test statistically represents in-situ conditions. The new direct shear pullout test apparatus developed in this research makes use of innovative design techniques in order to control and minimize identifiable boundary effects.

1.8 THESIS OBJECTIVE.

The objective of this research is to develop a test apparatus capable of isolating and/or eliminating the variables affecting pullout behavior of reinforcing inclusions embedded in round silica sand under both static and dynamic load conditions. To facilitate the development, tests were conducted to evaluate the performance of each individual component of the apparatus, as well as test for evaluating the functionality of the fully assembled test apparatus. The dynamic interface test apparatus is shown in Figure 1-6. Performance tests are used to appraise the individual components. Full-scale tests ensure that the assembled apparatus is fully operational and ready to pursue additional interface testing between reinforcing inclusions and sand under both static and dynamic loading conditions.

1.9 CHAPTER SUMMARY.

Geotechnical engineers currently have moderate but limited knowledge of the interdependent behavior occurring amongst the soil and reinforcement under static conditions; however, when it comes to dynamic behavior, the behavior is not well understood. The uncertainty results in designs with high factors of safety. Soil has considerable compressive strength, but failures often occur as shear bands propagate through the soil mass. By reinforcing the soil with embedded inclusions, the overall shear strength of the soil can be significantly increased. This has applications to foundations, retaining walls, and landfills. The shear stress is transferred from the soil to the inclusion, a very complex process that is affected by boundary conditions. Test scale also plays an important role in the validity of the experiments. Finally, all laboratory methods used to evaluate interface shear, fall into three basic categories, Equivalent Homogenization Methods, Explicit Modeling Methods, and Limit Equilibrium Methods.

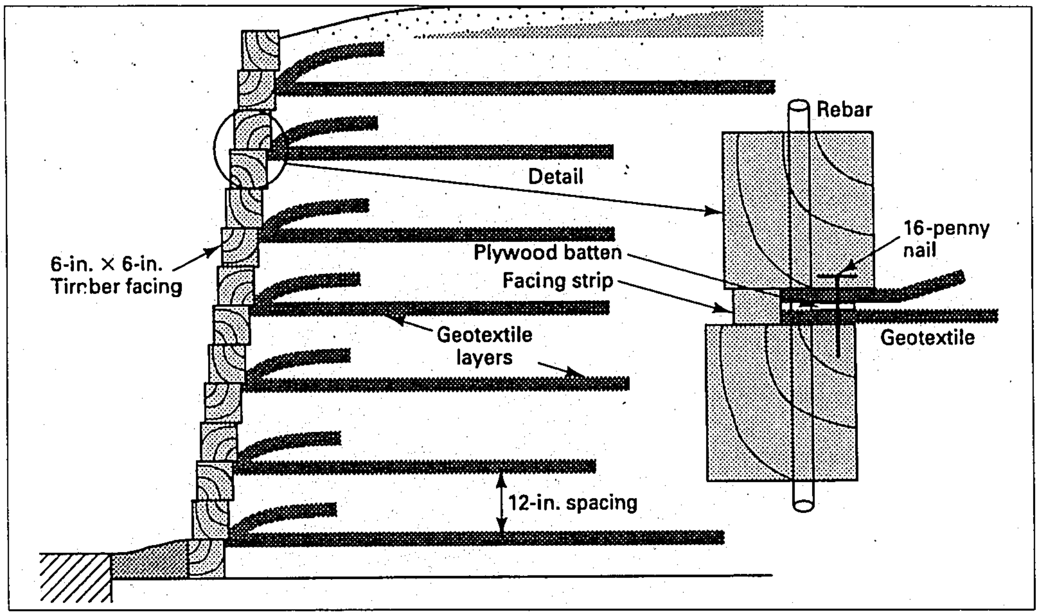


FIGURE 1-1

HIGHWAY ENGINEERING APPLICATIONS (FROM KOERNER, 1994)

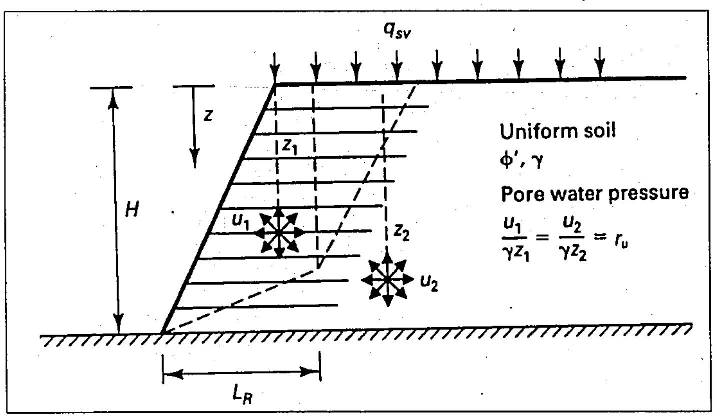


FIGURE 1-2

REINFORCED SOIL FAILURE ZONE (FROM KOERNER, 1994)

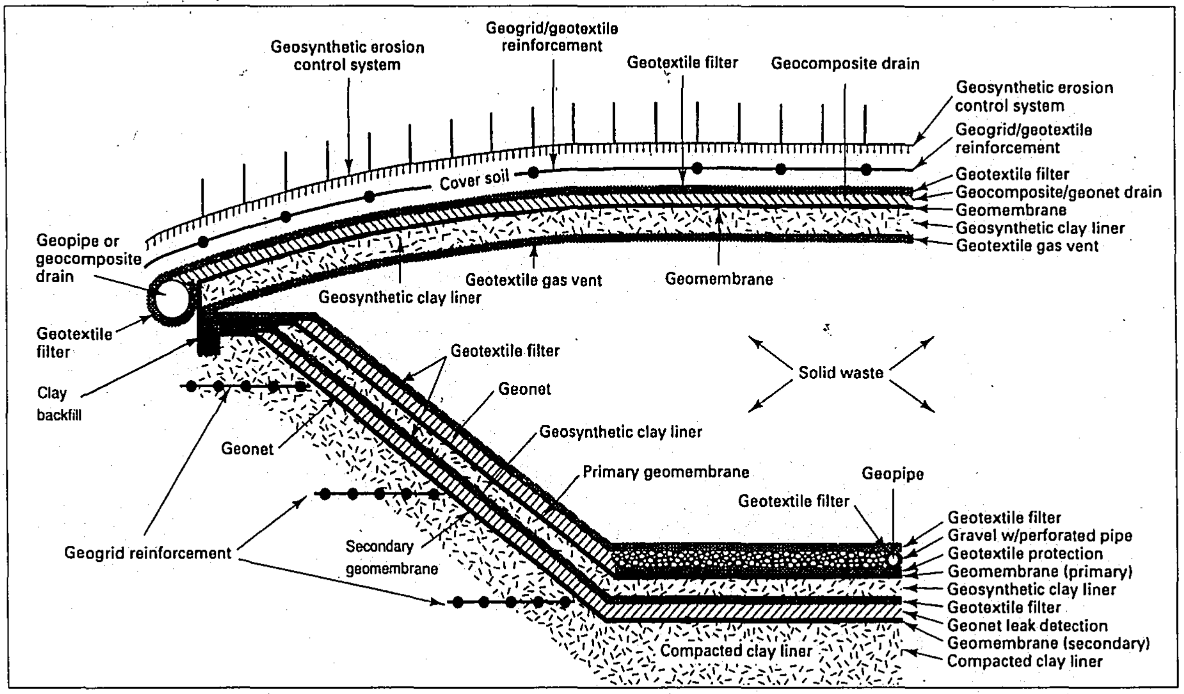


FIGURE 1-3

TYPICAL LANDFILL LINER SYSTEM (FROM KOERNER, 1994)

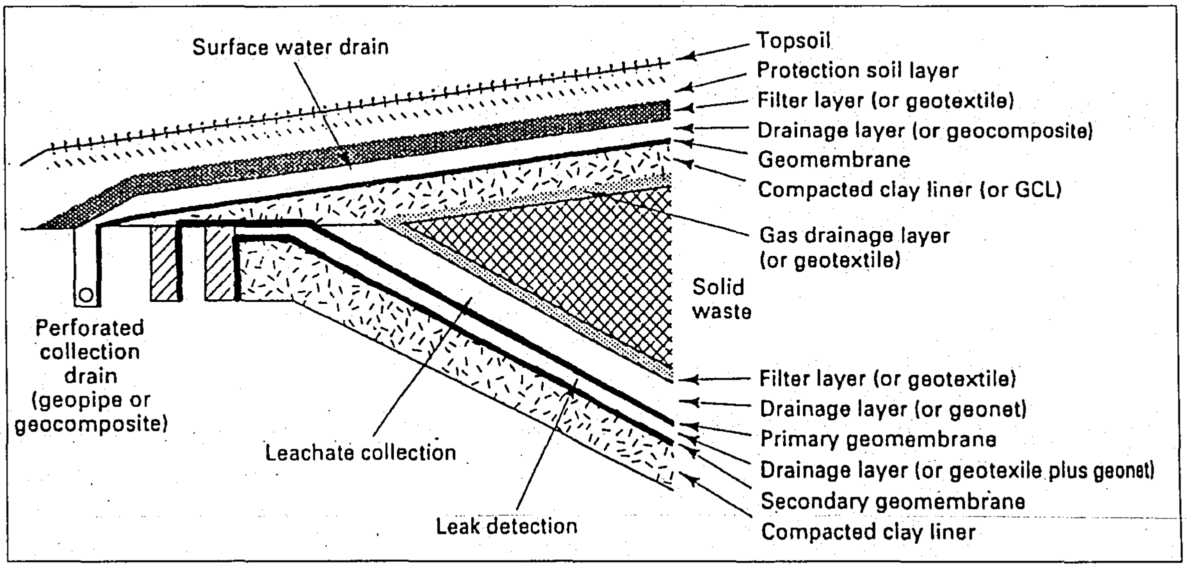


FIGURE 1-4

SOLID WASTE ACTING ON LINER SYSTEM (FROM KOERNER, 1994)

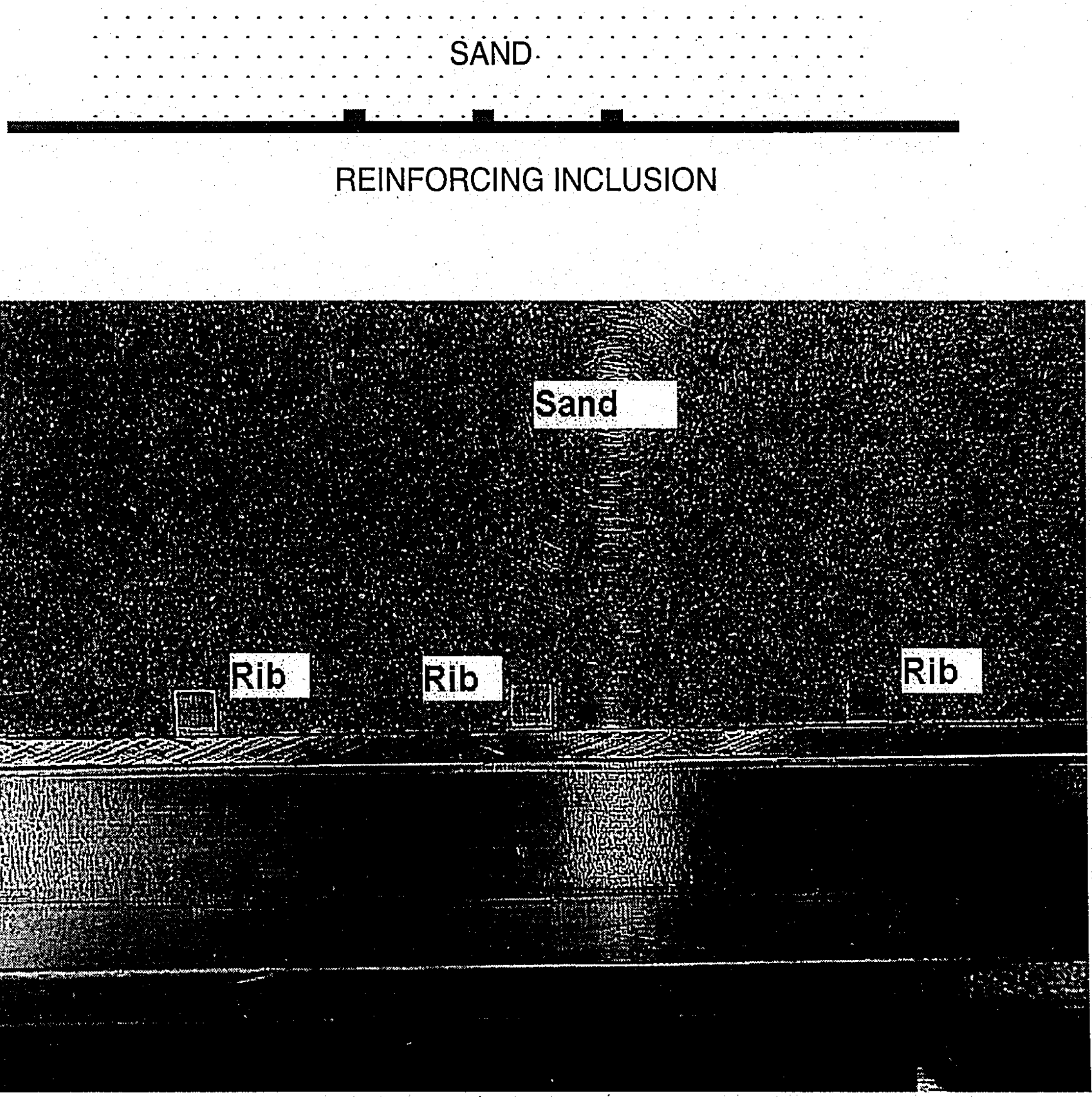


FIGURE 1-5

SAND-INCLUSION INTERFACE

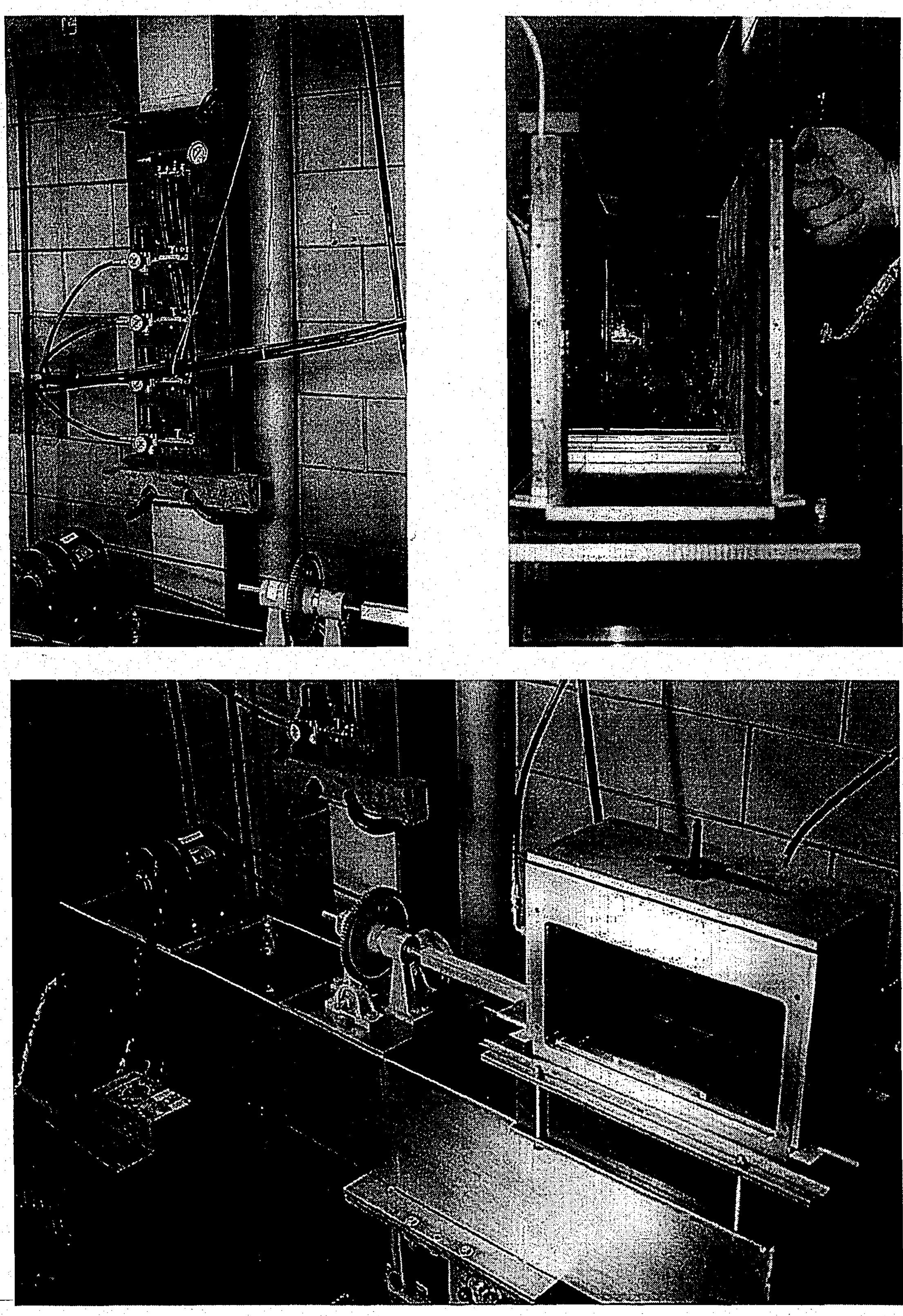


FIGURE 1-6

DYNAMIC INTERFACE TEST APPARATUS

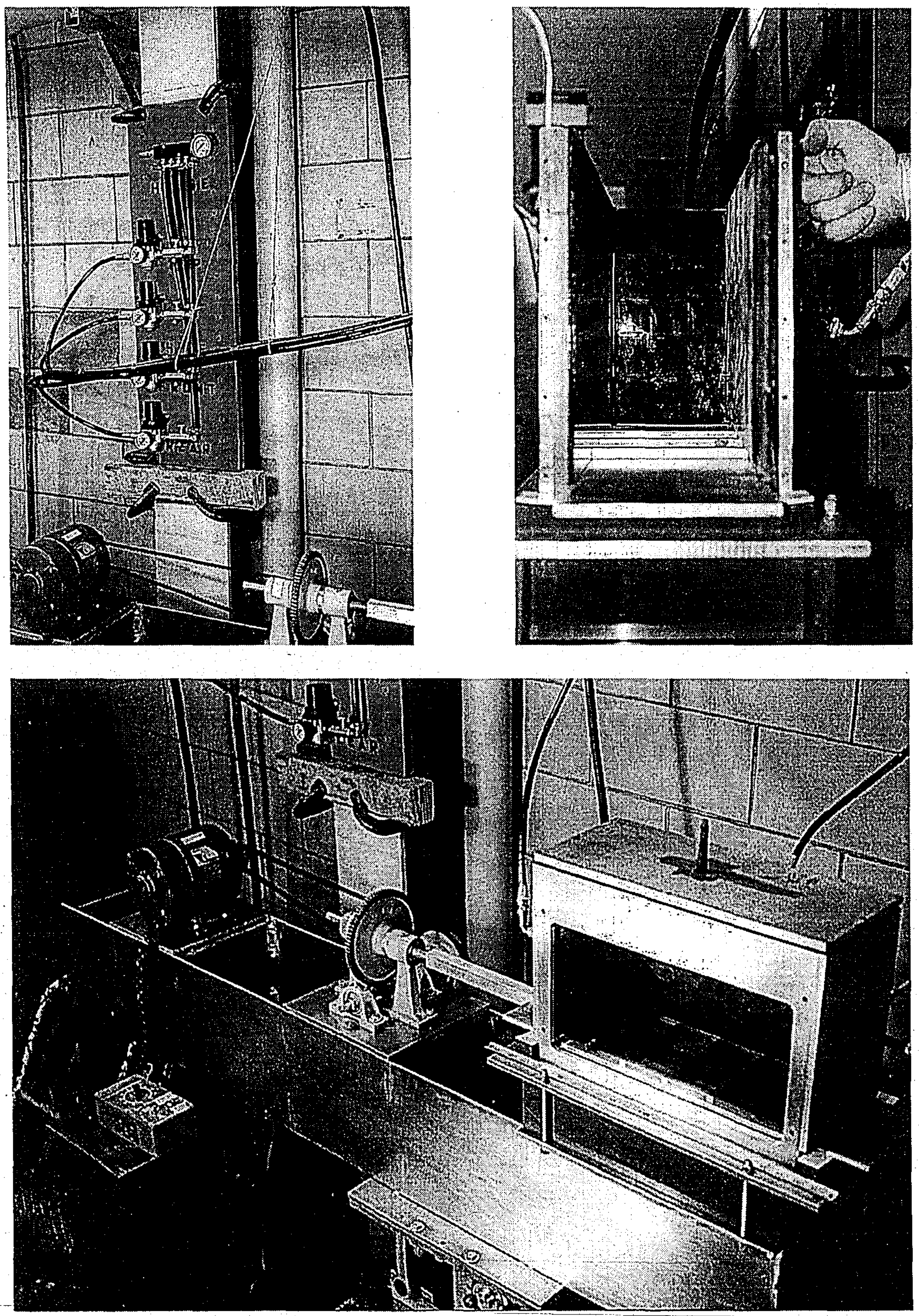


FIGURE 1-6

DYNAMIC INTERFACE TEST APPARATUS

CHAPTER 2

2 LITERATURE REVIEW.

This chapter reviews the most recent published developments related to dynamic interface testing between reinforcing inclusions and soil. Included in this literature review are static interface load transfer tests, static and cyclic pullout tests, and dynamic interface friction analysis between two planar reinforcements. The chapter is divided into three broad categories.

2.1 SHEAR LAG ANALYSIS OF PLANAR REINFORCEMENTS.

Abramento and Whittle (1995), present a new analysis method that is capable of describing the complete load transfer behavior of extensible, planar, reinforcements using idealized boundary conditions and shear lag approximations. The shear lag approximations take into account the development and distribution of tensile stresses and interface tractions along the inclusion allowing physical interpretations to be made of individual parameters without the complexities associated with non-linear algebra. The material properties, geometry, interface friction angle, and external consolidation stress state are related by analytical solutions to the pullout response, tensile stress, and the distribution of interface traction. By integrating elastic strains occurring within the inclusion, the pullout response is accurately depicted. The response is based upon the smooth and continuous distribution of tensile stresses and interface tractions throughout the inclusion. A concept dealing with the characteristic anchor length is used to explain the differences in distribution of tensile stress within the reinforcement. The differences are explained by equating the reinforcement length in the no slip zone to the length necessary to achieve full transfer of the tensile load acting at the sliding front.

The analysis assumes that the soil matrix and reinforcing material behave as linear, isotropic, and elastic materials. Consequently, the analysis becomes less reliable when there are significant zones of failure around the inclusion. The interface at the soil-reinforcement is assumed to act as a frictional boundary, characterized by a constant friction angle. No axial force is presumed to act on the end of the embedded specimen. Both the inclusion and the soil matrix have axial stresses that vary only in the horizontal direction.

Four phases of inclusion response are identified during pullout. Initially, there is no interface slippage between the sand and the inclusion. Next, an active slipping front progresses along the inclusion and an upper yield stress is detected. Thereafter, both active and passive slipping fronts are formed, characterized by two-way debonding subsequent to the passive slipping front intersecting the active slipping front resulting in maximum pullout resistance. Finally, after the local interface friction unfolds at all points along the inclusion, constant or residual pullout resistance is developed as full slippage occurs along the inclusion.

Abramento and Whittle (1995) perform all of the experiments used to validate the analysis with a new laboratory device referred to as the automated plane strain reinforcement (APSR) cell. Larson (1992) originally designed the APSR cell to measure the tensile stress transferred to the reinforcement while the surrounding soil is sheared in plane strain compression. Figure 2-1 illustrates a cross-section view of the ASPR cell. In the APSR-cell, the soil is confined by air pressure and is sheared by increasing the major principle stress through water bags at either end of the specimen. The cell maintains plane strain conditions by incorporating a unique system of active sidewall control. All of the contact surfaces are lubricated with a thin layer of silicone grease to minimize shear tractions. The lubricated surface tends to limit the average shear resistance due to the cohesive strength of the silicone grease (≈ 1.4 kPa). The front boundary conditions of the APSR cell are different from those assumed in the shear lag analysis, but the authors suggest from the available data that the discrepancy has little effect on the interpretation of the pullout experiments on either thin steel or 6/6 nylon sheets.

Results from the APSR cell confirm that interface slippage originates at first yield stress. At the active end of the inclusion where sliding begins, there is a non-linear distribution of tensile stress within the reinforcement and also local amplifications of interface shear and normal tractions. The maximum shear tractions are due to the local amplification of normal stress. The sliding front along the inclusion characterizes the progression of subsequent stages of the test. Stress conditions ahead of the sliding front are qualitatively similar to the pre-yield behavior. Sliding initiates at the passive end of the inclusion at the upper yield stress as the peak pullout resistance mobilizes followed by two-way debonding that is characterized with a noticeable reduction in pullout resistance. The two-way debonding is termed "snap through" by the authors. The tensile stresses are distributed linearly with increasing slip. Remarkably, the tensile stress is almost exactly linear at peak pullout load. Small non-uniformities are limited to the vicinity of the two sliding fronts.

2.2 PULLOUT TESTS TO INVESTIGATE LOAD TRANSFER.

Raju and Fannin (1993) describe results from displacement controlled tests involving large-scale pullout equipment. The testing device is composed of a pullout box, clamp assembly, hydraulic loading system, and a reaction frame. Figure 2-2 shows a schematic of the apparatus. All of the boundary conditions within the pullout box are strained controlled except for the top, which employs a water bag to create a stress-controlled boundary. Test specimens included rigid rough aluminum sheets, high junction strength geogrids, low junction strength geogrids, textured geomembranes, and smooth geomembranes, which were embedded in rounded silica sand for testing purposes. Measurements of the surcharge pressure, pullout force, pullout displacement, front wall pressure, displacement of the embedded end of the inclusions, and tensile strain were used in describing the pullout resistance; however, the primary variable in the test program involved the vertical effective stress.

The authors compared the behavior of smooth geomembranes versus textured geomembranes. Contrasting behavior was observed for the different types of geomembranes. First, the textured geomembranes exhibit steadily increasing pullout resistance without pronounced upward peaks toward constant limiting values. Second, a marked peak resistance followed by a lower limiting value characterized the smooth geomembranes. The smooth geomembrane did not develop as much pullout resistance compared to the textured geomembrane. However, increased confining stress affected the behavior for both textured and smooth geomembranes in similar fashions. Both types of membranes produce gains in the peak pullout resistance. Likewise, extensible membranes also require additional displacement to mobilize peak pullout resistance when the confining stress is increased.

Test results from high and low junction strength geogrids reveal that high junction strength geogrids exhibit a steadily increasing pullout resistance, up to a constant limiting value similar to the textured geomembrane. However, at high confining stresses, the pullout resistance produced from these geogrids is significantly lower than the values from textured geomembranes. Low junction strength geogrids exhibit a peak pullout resistance at very low confining stresses, but not at higher confining stresses.

All of the geosynthetics, which include textured geomembranes, smooth geomembranes, high junction strength geogrids and low junction strength geogrids, have similar behavior characteristics. All of the geosynthetics mobilize interface bond rather slowly compared to rigid rough aluminum sheets; therefore, geosynthetics will act as extensible sheets. Progressive strain in geosynthetic test specimens mobilizes the pullout resistance, with more marked behavior observed at higher confining stresses.

Rigid, rough aluminum sheets mobilize a slight peak resistance at low vertical effective stress and pronounced peak resistance without decreasing to a constant limiting value under moderate confining stress. The rigid, rough sheet mobilizes the interface bond much more rapidly than the geosynthetics. The authors also attached sandpaper to the rigid rough aluminum sheet in order to conduct sand-sand interface comparisons.

Several comments are included in their papers concerning different aspects of the test. First, relatively slow pullout rates do not affect the pullout resistance. Second, the front face of the pullout box experiences increments of horizontal stress as the pullout resistance is mobilized. Third, the stress is asymmetric on the front face of the pullout box above and below the inclusion. The asymmetry is caused from the lower boundary of the test being rigid, strain controlled while the upper test boundary is a flexible, pressurized bag (stress controlled). A larger increment of stress was detected above the inclusion with the stress-controlled boundary; however, the authors do not consider the influence of the localized anisotropic pressure conditions to be significant.

Raju and Fannin (1995) describe the incremental load transfer for cyclic load in geosynthetic materials and examine the manner in which confining stresses, specimen geometries, and loading frequencies influence mobilized pullout resistance. The testing apparatus incorporates a large pullout box, a reaction frame, a hydraulic actuator system, a large clamp assembly, and an automated electro-hydraulic system. The automated system permits for evaluation of either load controlled or displacement controlled tests.

Two different frequencies, 0.1 Hz and 0.01 Hz, produced very similar values of limiting pullout resistance at a confining stress of 10 kPa. Therefore, the authors postulate that generalized loading is insensitive to the range of frequencies encountered in the test.

However, the authors also noted that frequency affected the accumulated displacements occurring within the loading cycle and concluded that further testing is necessary to validate their claim, which was inferred from limited data.

2.3 DYNAMIC INTERFACE SHEAR STRENGTH OF GEOSYNTHETICS.

Yegian and Lahlaf (1992) studied the dynamic interface properties between an HDPE geomembrane and a non-woven geotextile using a simple experimental setup. The tests incorporate a geotextile fastened to the bottom of a concrete block upon which dead weights are placed. The dead weights are used to control the normal stress acting on the geomembrane-geotextile interface. Figure 2-3 depicts the test setup. The dead weights, concrete block, and geotextile are free to translate laterally across the surface of the geomembrane. The geomembrane is securely fastened to an aluminum shaking table that vibrates in the horizontal plane. A removable tub can be used in the test by bolting the tub to the surface of the shaking table. The tub allows testing of interface properties under submerged conditions. An electro-dynamic vibration exciter vibrates the table in the horizontal direction across frictionless, linear, bearing-pillow blocks contained in two stainless steel guide rails. The relative slippage between the concrete block and the shaking table is recorded using a linear variable displacement transducer (LVDT). Both the concrete block and the shaking table are instrumented with piezoelectric accelerometers for simultaneous measurements of acceleration. Figure 2-3 shows a force diagram for a typical geotextile-geomembrane dynamic interface test.

The tests measures the maximum shear transmitted to the concrete block as a function of the table acceleration, frequency of motion, normal stress, and dry versus submerged conditions. The authors found no significant differences between the dynamic interface friction angle at the start of sliding in the shaking table tests as compared with the static tests. Also, submerging the geotextile-geomembrane interface under dynamic conditions produced results similar to the static case, but is characterized by a slight decrease in the interface friction angle. A reduction in concrete block acceleration is noted when the concrete block slides relative to the geomembrane attached to the shaking table. The authors attributed the reduced block acceleration to the residual shear resistance, which is less than the peak shear resistance occurring before sliding initiates. However, the results indicate that the peak block acceleration increases slightly with increasing peak table acceleration. The authors discovered that in the range tested (2 Hz to 10 Hz) frequency has little effect on the peak block acceleration. Likewise, the effects of normal stress have no influence on increased peak block acceleration with increased table acceleration beyond the onset of sliding. The authors observed that slight increases in block acceleration and shear stress need to be further investigated.

Yegian et. al (1998) present a dynamic interface analysis between two geosynthetics that incorporates an equivalent spring and dashpot from generated hysteresis loops. Figure 2-5 illustrates the simple spring-dashpot model. The spring stiffness and the damping provided by the dashpot represent the geosynthetic interface and are used to describe an equivalent soil layer that may be used with a general purpose finite element code, such as SHAKE.

Damping is obtained from the following equation:

$$D = A_{4quad} \div (4 \times \pi \times A_{SpSt}) \quad (1)$$

Where,

A_{4quad} = The area in all four quadrants of the hysteresis loop.

A_{SpSt} = The area under the spring stiffness line.

$\pi = 3.14159$.

Figure 2-6 shows a typical plot from which the damping coefficient is obtained.

The authors do not elaborate on the damping parameter, but they do provide a much more detailed explanation of the stiffness parameter. The equivalent stiffness is defined as the slope of the line that intersects the two peaks on the force slip hysteresis loop. Figure 2-6 depicts the straight line with slope equal to the spring constant. The stiffness is a function of maximum transmitted acceleration, slip amplitude, and normal force. To avoid working with normal stress in the finite element analysis, the authors used normalized stiffness. At small base accelerations very little slip occurs and the behavior is rigid with very large stiffness. With increasing acceleration, the peak transmitted acceleration increases slightly, and a stick-slip behavior is observed at the time of reversal.

2.4 SUMMARY OF LITERATURE REVIEW.

Three broad categories of research related to dynamic interface testing are reviewed in this chapter. The review includes recent research concerning static interface friction tests, static and cyclic pullout tests, and dynamic interface friction tests between planar reinforcements. Abramento and Whittle (1995) discovered that four phases of the pullout response can be identified: 1.) No interface slippage, 2.) Active slipping front, 3.) Peak Resistance followed by both active and passive slipping fronts, 4.) Residual resistance. Raju and Fannin (1995) encountered progressive strain development in extensible inclusions, but found that the rigid aluminum sheets mobilize interface bonds along the sheet simultaneously. Also of note was the evidence indicating that slow rates of pullout displacement as well as low frequencies of cyclic loading have little effect on the results. Yegian and Lahlaf (1992) evaluated the maximum shear transmitted between two geosynthetics and used the test parameters in a general-purpose finite element software program. No information related to the subject of dynamic interface testing between soil and reinforcing inclusions is currently available.

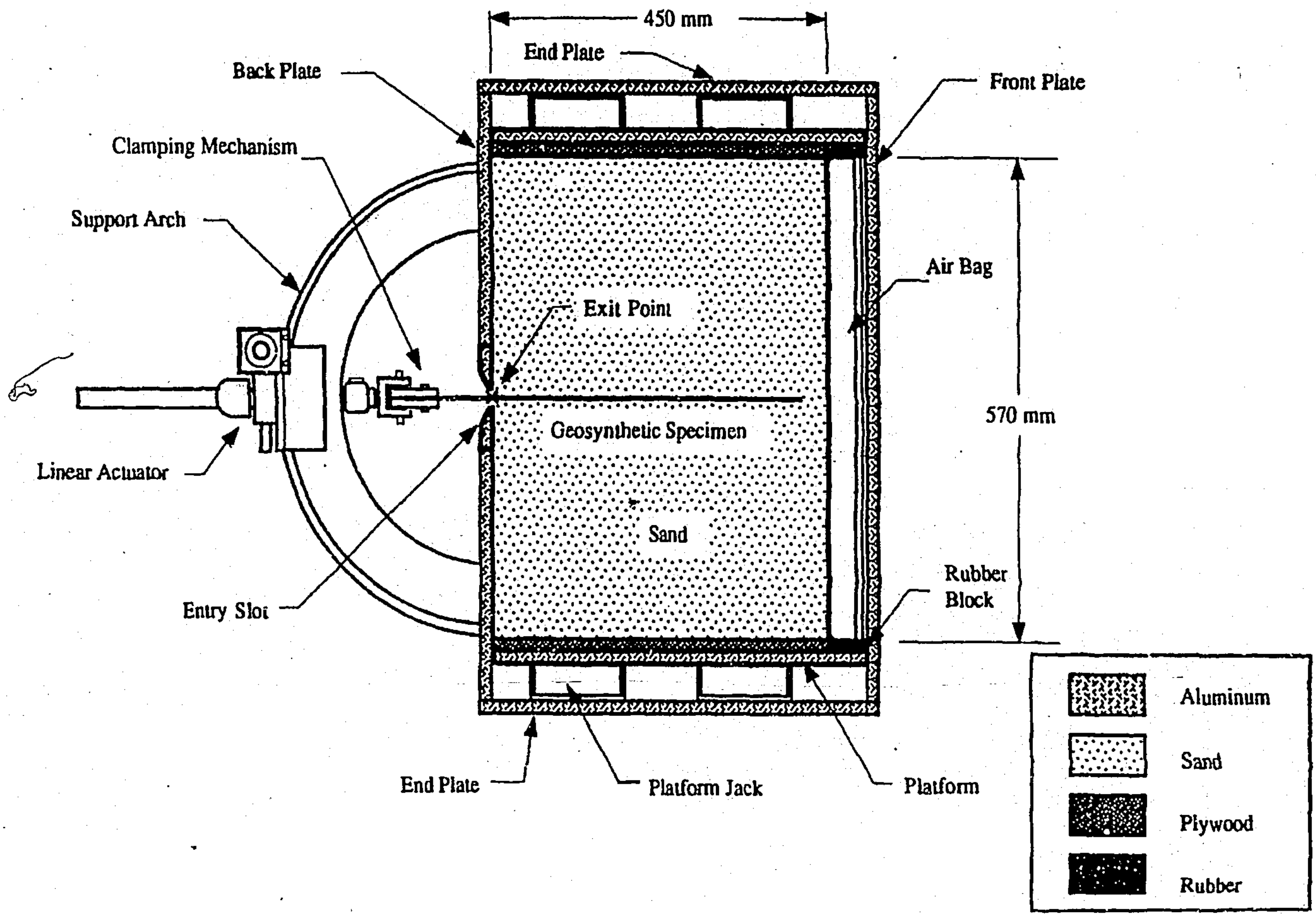


FIGURE 2-1

AUTOMATED PLANE-STRAIN REINFORCEMENT CELL (FROM CHAUHAN, 1995)

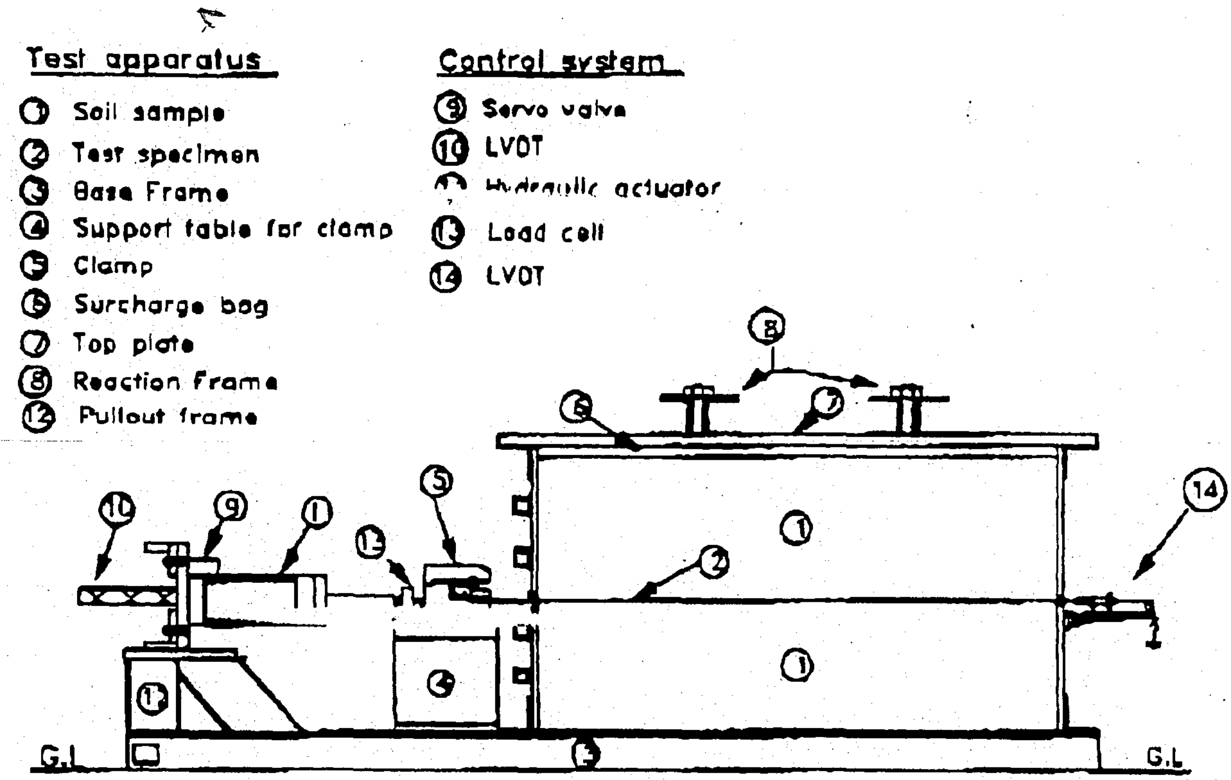


FIGURE 2-2

LARGE SCALE PULLOUT BOX AND REACTION FRAME (FROM FANNIN, 1997)

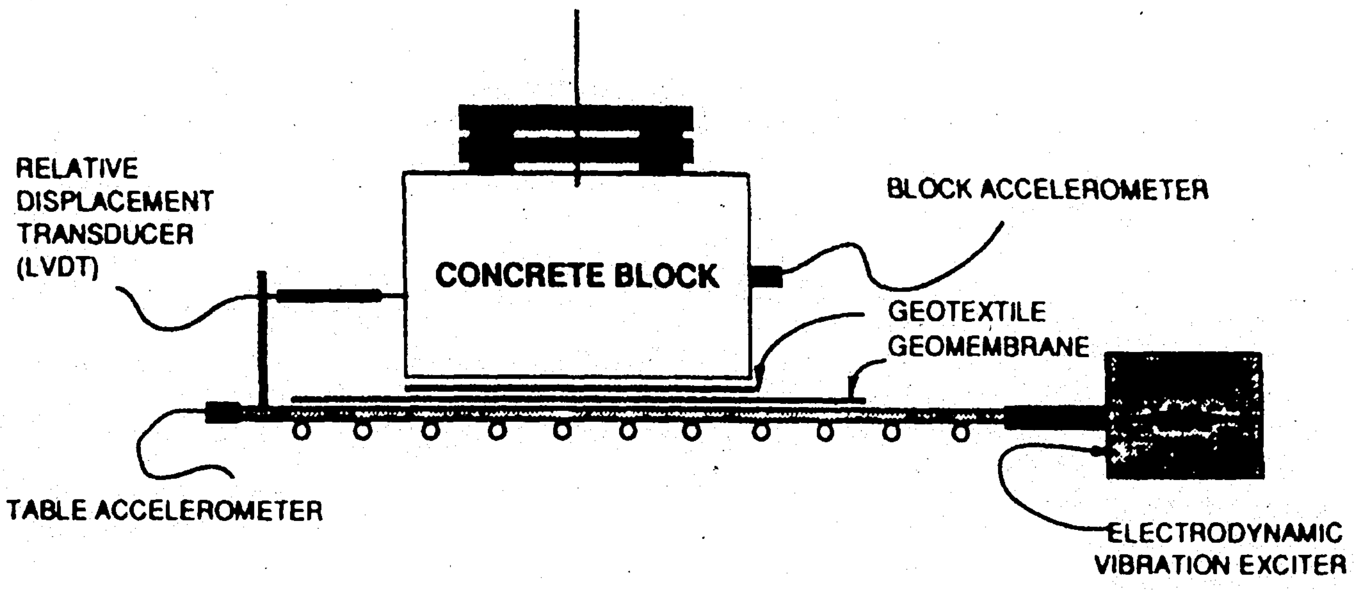


FIGURE 2-3

SHAKING TABLE FACILITY (FROM YEGIAN, 1998)

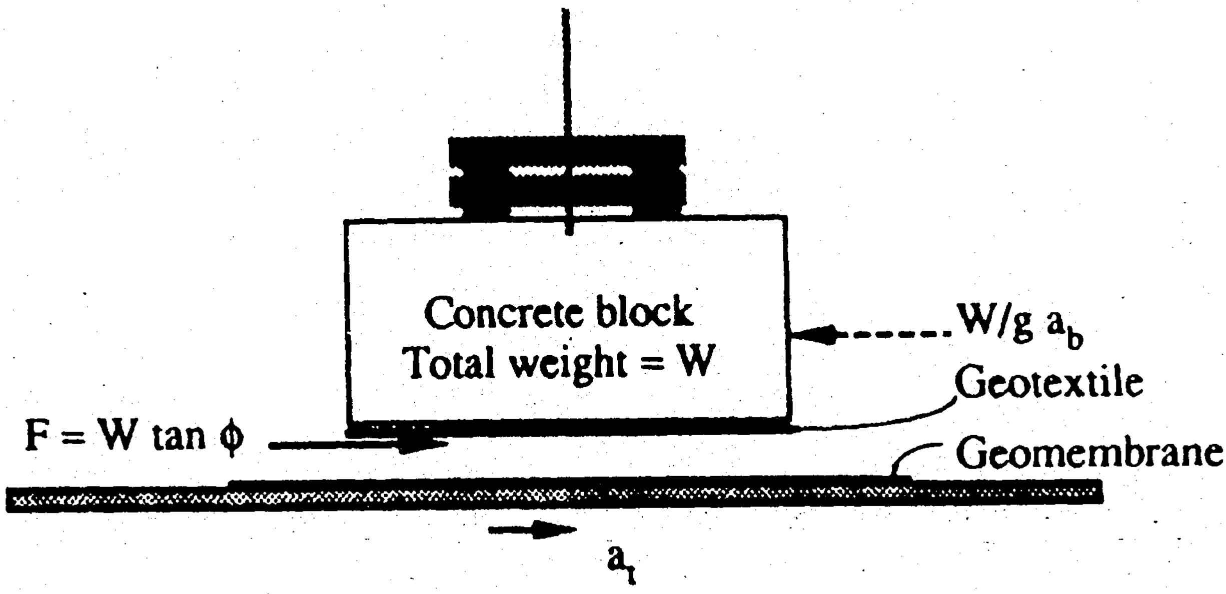


FIGURE 2-4

GEOTEXTILE TO GEOMEMBRANE FORCE DIAGRAM (FROM YEGIAN, 1998)

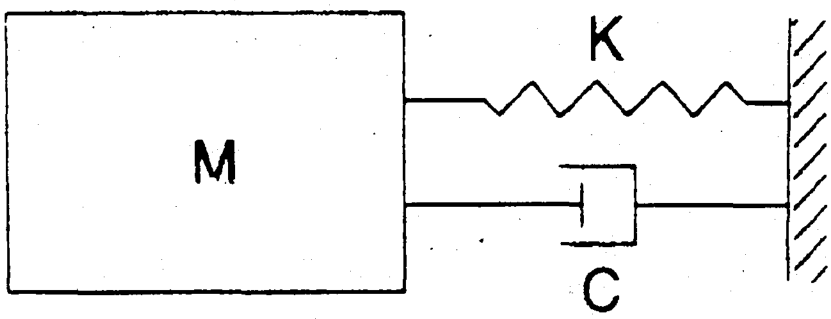


FIGURE 2-5

GEOTEXTILE TO GEOMEMBRANE FORCE SLIP MODEL (FROM YEGIAN, 1998)

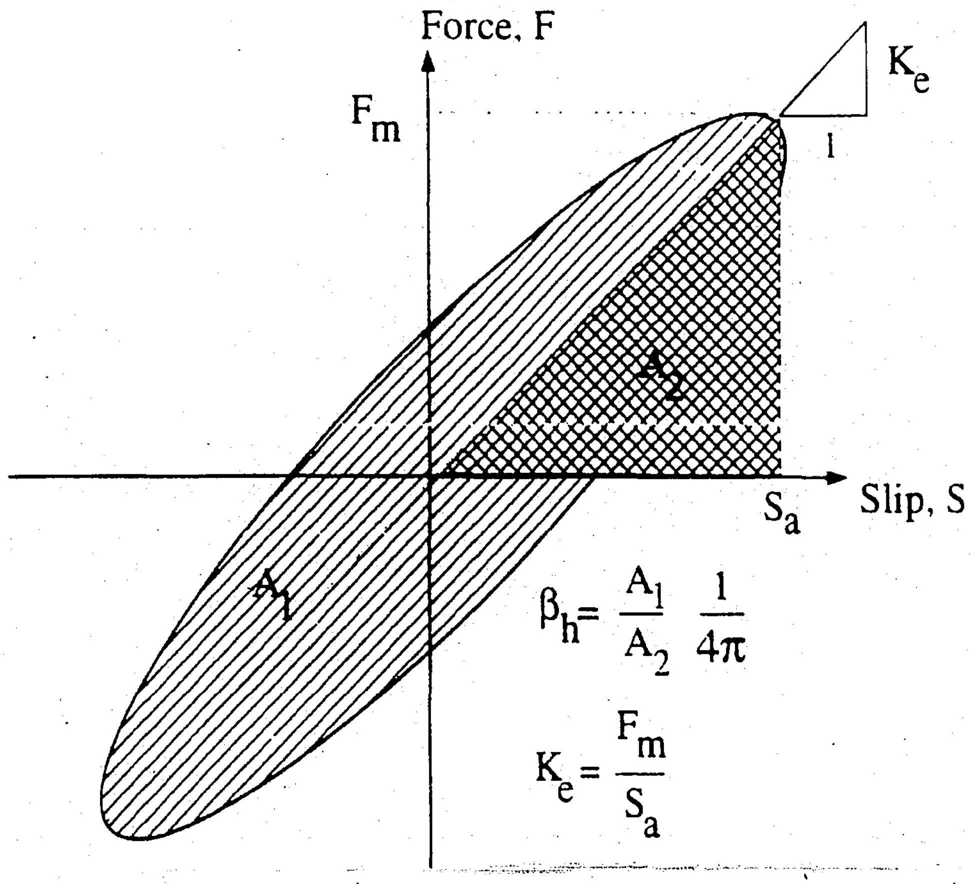


FIGURE 2-6

STIFFNESS AND DAMPING PARAMETERS (FROM YEGIAN, 1998)

CHAPTER 3

3 EQUIPMENT AND PROCEDURE.

This chapter describes the design and fabrication of individual components that comprise the dynamic interface test apparatus (DITA). The DITA is shown in Figure 3-1. Since not all of the equipment used to construct the dynamic interface apparatus is freely available, a distinction will be made between the specially fabricated equipment and acquired equipment. After presenting the main goals identified for the dynamic interface test apparatus, technical descriptions of the materials used are itemized. This chapter also provides an outline of the dynamic interface test procedures.

Acquired equipment was purchased from vendors after it meets the specifications set forth in the conceptual planning stage. For example, a fundamental goal set forth in the conceptual planning stage stipulated that the equipment must be capable of implementing various boundary conditions in order to determine their effect on interface behavior. The acquired shake table is capable of implementing various dynamic loads at different frequencies and amplitudes. This allows tests to be performed at various amplitudes of vibration and/or various frequencies of vibration.

The fabricated equipment was constructed to meet the specific goals identified during the conceptual planning stage. For instance, the walls of the dynamic pullout shear box are designed to have bolted joints rather than welded joints. Bolting allows the front and rear slot faces to be removed, altered, reattached, and re-tested under the same dimensions and physical conditions.

3.1 GENERAL REQUIREMENTS.

The conceptual design stages of the dynamic interface testing apparatus identified several fundamental concerns. These fundamental concerns stem from an attempt to simplify the mathematical complexities involved in the data analysis and reducing undesirable boundary effects.

Uniformly imposed confining stresses are required in order to keep the analysis as simple as possible. This is also accomplished by maintaining a constant area in which the stresses act. Stresses that are uniformly imposed reduce the need for using complicated mathematical formulations. Keeping the normal planar surface area of the embedded inclusion constant throughout the progression of the test also helps to simplify the analysis by eliminating the need for area corrections. Corrections to the area are needed when the area changes throughout the test and stress determinations are required. One way to maintain a constant loaded area is by having both a front and rear slot incorporated into the pullout box. The inclusion extends all the way though and just beyond the box.

After evaluating problems that would complicate the analyses, the boundary conditions known to affect interface test behavior were addressed. Complications arise from several factors including slot configurations, clear distances, and box size.

Slots in the pullout boxes allow the inclusion to be removed from the box while the tests are conducted; but at the same time, the slots must also serve to limit the amount of soil escaping between the inclusion and the pullout box. Another problem indirectly associated with slots is the shear stresses that builds up above the front wall slot during pullout tests. Friction occurs between the soil and wall material as the inclusion progresses towards the front of the pullout box. This friction is an undesirable boundary effect because it does not model insitu conditions. To help reduce friction effects, three different types of slot configurations have been previously developed by others; however, there is still no consensus as to which type of slot provides the best results.

Another potential problem with the pullout test is the clear distance separating the outside edge of the embedded inclusion and the inside wall of the pullout shear box. Shear stresses form along the outside edge of the reinforcing inclusion and the inside wall of the pullout box. These stresses develop as a result of the mobilized friction. The friction accumulates as a passive plug that is formed in the sand. The dimensions of this plug depend on the soil grain size. The size of the resistance plugs generally increases with increases in soil grain size. When the plugs become thick enough to induce pressure on the inside wall of the pullout shear box, the outcome of the interface test is notably affected.

Finally, the geometry of the pullout box should minimize scale effects. The scale of the test governs whether the test results recreate realistic construction/insitu conditions. For example, the volume of confining sand relative to the volume of a very stiff reinforcing inclusion in the test apparatus needs to be compared with the volume fraction of inclusion to sand encountered in actual field conditions. The volume of the pullout box should be roughly equivalent to the volume contained between the reinforcement spacing typically used by earth system designers.

3.2 MATERIALS.

Most of the equipment used for conducting this research had to be specially designed and fabricated. Material selection was an important consideration. The pullout shear box, shake table mounting base frame, and reinforcing inclusions are constructed from sheets of wrought, heat treated aluminum. Furthermore, the pullout shear box incorporates many materials such as acrylic, untreated glass, clear polycarbon, butyl rubber, polyvinyl chloride, and polytetrafluoroethylene. These materials are required to create the required boundaries within the box.

Computer software programs were used during the material selection and design phase of the project. SAP2000, a structural analysis program, features many types of joint constraints as well as frame and shell structural elements. Plane elements are used to model both plane-stress and plane-strain behavior in two-dimensional solids. Plane element stresses are evaluated using the standard 2-by-2 Gauss integration points contained on the elements and then extrapolated to the joints. Plane elements allow three translational degrees of freedom at each connected joint. However, rotational degrees of freedom are not activated in the analysis. There are several physical properties assigned to the material, including; the modulus of elasticity, shear modulus, Poisson's ratio, coefficient of thermal expansion, mass density, and weight density (Computers and Structures, Inc., 1997).

3.2.1 ALUMINUM.

Aluminum alloys were used due to their light weight and high strength. Aluminum is also easy to fabricate and is highly resistant to corrosion. Selection of the proper alloy meeting specific application criteria depends on strength, durability, and economic feasibility. Availability of the alloy tends to limit the proper selection, as do the methods employed to fabricate the material. With the proper alloy and temper choice, a variety of forming methods/operations can be performed with aluminum.

Aluminum can be machined using all of the common methods associated with typical metal shop machinery; however, the tools should be specifically ground with keener cutting edges and more side and top rake. Straight cuts are easily made on aluminum using stationary or portable circular saws, while curved and coping cuts are made with band saws. High-speed blades accompanied by soluble oil type lubricants are recommended for all types of aluminum work.

Jointed connections for aluminum are produced very similar to other common metal connections. The recommended drill speeds for boltholes in the primary load carrying members are approximately 50 percent greater than those normally used for steel. Furthermore, torch, electric arc, and resistance welding methods can all be used to connect certain aluminum alloys. However, the designer must be aware that welding tends to reduce the strength of tempered aluminum due to softening effects of the applied heat.

When designing with aluminum, greater deflections should be anticipated because the modulus of elasticity for aluminum is much lower than other metals such as steel. With aluminum construction, the allowable deflections may ultimately govern the design (ALCOA Aluminum Company of America, 1960).

After considering the various engineering properties of aluminum and many of the available alloys, a heat-treated wrought aluminum alloy was chosen for the metal components of the dynamic interface test apparatus. These components include the walls of the pullout shear box, the shake table mounting base frame, the inclusions, and the pullout connecting mechanism. The sheets and bars were designated as per the manufacturer as *6061-T651*. This type of aluminum is widely used and typically recommended for heavy-duty structures where resistance to corrosion is necessary. Typical applications include pressure pipes, railroad cars, and applications in marine environments.

3.2.2 BUTYL RUBBER.

Butyl rubber is a combination of vulcanized hydrocarbon polymers that are low in saturation. This rubber may be easily cut into patterns and then vulcanized creating airbags of various sizes and shapes. Butyl rubber was used as the outer membrane of the airbags because this type of synthetic rubber is used for products that must be chemically stable and resistant to gas permeation such as the inner tubes of pneumatic tires. The degree of gas impermeability is very remarkable. The air retention of butyl rubber is eight times greater than that of natural rubber. Furthermore, ordinary sheets of butyl rubber are soft, flexible, extensible, and elastic. Butyl rubber also has considerable strength and toughness. Butyl rubber has high tear resistance after aging with time. After butyl rubber is stretched, it retracts quickly. Finally, butyl rubber is considered to be chemically inert for most practical applications (Thomas and Sparks, 1954).

3.2.3 CLEAR POLYCARBON.

Clear polycarbon is used as the material for constructing the internal supporting structures in the airbags. Clear polycarbon can be easily fused together with chemical compounds. After setting, the joints become as strong as the original material. Clear polycarbon has properties that are very similar to acrylic. However, clear polycarbon may be more appropriate for pressure applications because of a slightly greater ductile behavior over other inexpensive, chemically-fused plastics.

3.2.4 ACRYLIC.

Commercial polymethylacrylate, *acrylic*, was used in the composite window of the pullout shear box for added strength. This material is hard, rigid, and transparent with extremely good weathering resistance. It is superior to untreated glass in terms of impact resistance. The polymers absorb very little light, roughly 4 percent reflection of normal incident light at each air-polymer interface. The transmission of normal incident light through a parallel sheet of acrylic material free of blemishes is about 92 percent (Brydson, 1995). Acrylic is also very easy to fabricate.

3.2.5 UNTREATED GLASS.

Untreated glass was used at the sand interface of the composite window to reduce scratching and friction. Glass has greater scratch resistance than other inexpensive, commercially available clear plastics. Also, the coefficient of friction for glass is much lower than most clear plastic.

3.2.6 POLYTETRAFLUOROETHYLENE.

Polytetrafluoroethylene is used to reduce friction between moving parts inside of the pullout shear box. Polytetrafluoroethylene is a tough, flexible, non-resilient material of moderate tensile strength having excellent resistance to heat, chemicals, and to the passage of electric current. The coefficient of friction is unusually low, lower than any other solid. The coefficient of friction often quoted between is 0.02 to 0.10 for polymer to polymer interface (Brydson, 1995).

3.2.7 POLYVINYL CHLORIDE.

The pullout shear box spacer was made from polyvinyl chloride. The properties of polyvinyl chloride, commonly called PVC, vary tremendously depending on the additives used in the compound. PVC is available in hard, durable sheets of varying thicknesses.

3.3 FABRICATED EQUIPMENT.

The pullout shear box, reinforcing inclusion, shake table mounting base frame, pressure bags, window components, pullout shear box spacer, and friction liners were specially designed and fabricated because no commercially available "off-the-shelf" products were readily available. These items were fabricated from the aforementioned materials.

3.3.1 PULLOUT SHEAR BOX.

Several finite element analyses were performed using SAP 2000 software to compare the strength and deflection using the various materials and weighing this against the weight, cost, and fabrication criteria. Sheets of 6061-T651 aluminum were chosen as the material for the walls of the pullout shear box. Cost was not a large factor because there is no appreciable cost difference between any of the readily available materials having the required strength. However, the cost that is required to obtain the thickness to limit deflection rule out many plastic materials. Many of the metals were also eliminated since the bolted box joints require a minimum plate thickness. This would have resulted in a dramatic increase in weight. The weight would have been too large for the available shake table. Therefore, aluminum was chosen for the pullout shear box.

Previous research has revealed several problems with conventional pullout boxes. Figure 3-2 illustrates the main distinctions between conventional pullout boxes used in previous research by others. Conventional pullout boxes have soil placed above and below the reinforcing inclusion. This creates pressure bulbs as a result of asymmetric pressure distributions that are caused by lower strain boundaries and upper stress boundaries.

Vertical pullout alignment is difficult to control when there is soil both above and below the inclusion. In order to eliminate this problem, the pullout shear box used in this research only has sand on the top of the reinforcing inclusion. The underside of the inclusion slides across a frictionless sheet of polytetrafluoroethylene, which is affixed to the bottom of the pullout shear box. Conventional pullout boxes also allow soil to come into contact with the edge of the reinforcement. This produces wedging and affects the test results if the clear spacing is not sufficient. To eliminate problems with the clear spacing, the internal sidewall components are designed to rest on top of the inclusion along the edges thereby preventing the soil from coming into contact with the soil. The components are designed to seal off a quarter inch of the outside edge of the inclusion from the sand, as well as allow the inclusion to be pulled out from underneath the components. The components rest on top of the inclusion as it is being withdrawn from the pullout shear box similar to the operation of a treadmill. Figure 3-3 shows the internal components resting on the inclusion. With these internal components, there is no need to be concerned with the size of the soil grains or the amount of friction accumulating on the sidewall from the mobilized soil plug.

An additional feature of the pullout shear box over convention pullout boxes is the large side composite window as shown in Figure 3-4. The hole for the window is cut out of the aluminum side plate to allow visual inspection during the pullout process. Eventually, digital-imaging equipment will be placed outside the window and will be incorporated into the data collecting process for the dynamic interface shear-testing program.

The pullout shear box uses both front and rear slot-cutouts so that the area affected by stress remains constant throughout the test. Figure 3-5 shows an elevation view from one end of the pullout shear box depicting a slot-cutout. This allows the reinforcing inclusion to be pulled out of the box while the planar area in contact with the confining sand remains constant. As indicated earlier, this will simplify test analysis. The inclusion extends two inches beyond both the front and rear wall of the pullout shear box as shown in Figure 3-4. At no time during the test does the area in contact with the confining sand change.

The pullout shear box is also designed to function properly at internal pressures up to 30 psi. Thirty psi corresponds to effective stresses produced in sands that are 35-40 feet deep. This is greater than stresses actually encountered in typical reinforced earth applications, which typically do not exceed 20 psi.

The front, rear, left side, and top of the pullout shear box contain single 11/16th-inch holes. These holes allow the valve stems of the internal pressure bags to penetrate all the way through the aluminum plates to the outside where air hoses can be attached and used to inflate the bags. Figure 3-6 illustrates a typical valve stem hole.

3.3.2 REINFORCING INCLUSIONS.

Inclusions used in reinforced earth applications can vary from being very stiff to flexible. When an inclusion is very stiff relative to the soil it may be considered rigid or ideal. Ideal inclusions tend to simplify the analysis necessary to understand inclusion-soil interaction under dynamic loading conditions. Flexible inclusions (also called extensible) tend to transfer strain in a more complicated fashion.

Metals are rigid compared to soil stiffness and represents an ideal inclusion. The ideal reinforcements are constructed from 6061-T651 aluminum sheets. Constructing the reinforcing inclusions from aluminum also ensured that the weight placed on the shake table would be kept to a minimum.

The surface geometry of these ideal inclusions can be modified in order to assess effect of rib height to spacing ratio on the pullout behavior. There are three sets of holes so that different rib sizes may be attached to the planar inclusion. Hence, the effects of rib height to rib spacing can be studied. Figure 1-5 illustrates the geometric surface of a typical ideal inclusion. This figure also illustrates that a number of geometric effects can be ascertained.

The device can also accommodate flexible inclusions for subsequent research to determine the dynamic and static effects of testing conditions. As mentioned previously, however, flexible inclusions transfer stress in a more complicated process. Strain, elongation, and material properties must be carefully evaluated.

3.3.3 SHAKE TABLE MOUNTING BASE FRAME.

The shake table mounting base frame houses the pullout shear box, pullout apparatus, and electric motor. The frame is shown in Figure 3-1. The frame is designed to be lightweight because of the substantial cost for dynamic excitation equipment that is needed with the increasing weight. The frame also has to be sufficiently rigid to limit the amount of deflection between the pullout shear box and the mechanical pullout apparatus. To achieve the lightweight shake table mounting base frame that limits the amount of deflection, two 6061-T651 aluminum plates were welded parallel to each other. These welded connections allow the thickness of the plates to be considerable thinner than bolted connections.

Bending deflection is a primary concern because the frame on top of the shake table supports the pullout shear box, mechanical pullout assembly, and electric motor. To ensure the most efficient beam design, the material needs to be placed furthest from the neutral axis. A simple beam analysis demonstrates that two very thin, comparatively wide, 6061-T651 aluminum plates are sufficient for limiting deflections to less than 0.01 inch.

In order to ensure that the web has sufficient rigidity, the aluminum plates are welded parallel to each other with cross bracing spaced under the ends of the plates supporting the pullout shear box, mechanical pullout assembly, and electric motor. The welding process is known as Tungsten Inert Gas (TIG) welding.

3.3.4 PRESSURE BAGS.

A fundamental concern for the confining pressure is uniform application of stress to the sand in order to simplify the analysis. Figure 3-7 illustrates a typical internal airbag frame. Fundamentally important to the performance of the device is uniformly distributing the confining pressure to the soil. To ensure uniform pressure distribution, the airbags must be able to supply external stress along the entire boundary of the confined sand. One way to accomplish this is to require the flexible airbags to maintain a predefined shape and surround the sand. Additionally, uniform pressure distributions are created by stress boundaries. These types of boundaries must be able to deflect and conform to the sand.

To ensure that the pressures would be uniformly distributed along the entire edge of the sand surface, internal frames and flexible exterior membranes were used. The internal frames are incorporated into the bags to maintain predefined volumetric shapes. The frame system allows the passage of air between interior elements with holes drilled into the internal members. When the inside of the pullout shear box is filled with sand, airbags without supporting mechanisms tend to wrinkle and dislodge. This prevents even pressure distributions. Additionally, the predefined shapes assist the operator while assembling the outer aluminum wall components of the pullout box. Metal can easily pinch and even puncture the soft, flexible air pressure bags. The internal frames make flexible membrane liners easier to position in the pullout shear box. Clear Polycarbon was used to construct the internal support frames. The frames are fastened together using chemical fusion.

Also, to provide uniform distribution of pressure, the pressure bags must conform to the shape of the soil particles. This requires membrane materials that are soft, flexible, extensible, elastic, tough, tear resistant, and most of all, fairly impermeable to gas. To achieve this, thin sheets of butyl rubber (1/32 inch) are used as the liner. These thin sheets deflect and conform to all sizes of coarse-grained soil.

3.3.5 COMPOSITE WINDOW.

The window components are constructed from materials that allow observation of the sand grain displacements as the test is conducted. The materials used for the window must transmit light and have sufficient strength while limiting deflection. Since the window rests against the abrasive sand, the window must minimize scratching and wall friction. In order to meet these requirements, two materials are used for the composite window as shown in Figure 3-3. Both materials must transmit a large amount of light. The material used to provide strength and limit deflection is acrylic. Acrylic is placed adjacent to the aluminum plate with the window cutout. The material interfacing with the sand is untreated glass. Untreated glass is relatively hard and limits the amount of scratching. It also has a lower coefficient of friction than the acrylic. The composite window is shown in Figure 3-8.

3.3.6 PULLOUT SHEAR BOX SPACER.

The requirements for the spacer that elevates and aligns the pullout shear box with the mechanical pullout apparatus are relatively simple. The spacer is shown in Figure 3-8. The pullout mechanism is from a motorized direct shear device. In order to precisely align the reinforcing inclusion and the pullout mechanism, the pullout shear box was raised 4.1 inches above the shake table mounting base frame. Therefore, the spacer can be any inexpensive, lightweight material that is sufficiently stiff and easy to fabricate. Polyvinylchloride meets these requirements.

3.3.7 FRICTION LINERS.

Sheets of Polytetrafluoroethylene were used to line the various surfaces in the pullout shear box. These surfaces must have low coefficients of friction to limit friction between the various components of the dynamic interface test apparatus. On the bottom of the pullout shear box, the inclusion slides across the friction liner. Therefore, soil only comes into contact with the top of the inclusion in order to eliminate asymmetric stress distributions.

3.4 PURCHASED AND ACQUIRED EQUIPMENT

Some of the equipment used in constructing the dynamic interface test apparatus is readily available from vendors and can be purchased as an "off-the-shelf" item. Material selection is not important for this equipment as long as the equipment meets or exceeds the performance specifications set forth in the preliminary design.

3.4.1 AIR PRESSURE SYSTEM.

The air pressure system is composed of air hoses, manifold, gauges, and regulators that supply air to the pressure airbags. The air pressure system is shown in Figure 3-9. The system connects to a quick disconnect on the manifold where the air is routed to a 150-psi gauge and four push on hose fittings. Four short hoses connect the hose fittings to four valves and then four regulators. Each regulator is equipped with a 30-psi gauge. The four regulators connect to the valve stems of the four pressure air bags by means of 8-foot long threaded hoses. This allows interface tests to be conducted under isotropic or anisotropic pressure conditions.

3.4.2 PULLOUT ASSEMBLY AND MOTOR.

The pullout assembly and motor are from an existing direct shear machine. The pullout assembly and motor are shown in Figure 3-1. The electric motor produces 1/8th horsepower and can be operated at variable speeds through a rate control box. The pullout assembly consists of a system of mechanical gears and a pulley.

3.4.3 DATA ACQUISITION.

Pullout force and displacement measurements are required for dynamic interface testing. The dynamic interface-testing program focuses on determining the differences between stress strain behavior under static and dynamic loading. Later, as the testing program develops, data acquisition may include accelerometers, pressure transducers, and digital imaging data of particle displacements at the soil-inclusion interface.

3.4.4 SHAKING TABLE.

The shaking table produces simple harmonic motion in the horizontal direction. The shaking table is shown in Figure 3-1. The frequency is adjustable from 10 cycles per second to 60 cycles per second while the machine is in operation. The displacement can range from 0 inches to 0.150 inches. The amplitude of vibration is equal to one half of the displacement. The table is equipped with a 1-1/2 H.P., 3-phase, 220-volt A.C. motor.

The vibration of the shaking table must not be transmitted to the base of the machine or the foundation. The machine foundation needs to be substantial so that extraneous vibrations are minimized. Otherwise, energy is transmitted to the machine base and foundation reducing the amount supplied to the test specimen. The foundation should be heavy, sturdy, and preferably located in the basement where the floors and walls are most heavily reinforced. Satisfactory results occur with a foundation that weighs at least ten times as much as the combined weight of the table and specimen (All American Tool & Manufacturing Company, 1961).

3.5 ELECTRICAL REQUIREMENTS.

The electrical needs for the shake table, electric pullout motor, and data acquisition system were not compatible. The shake table requires 220 volts. The electric pullout motor operates on 110 volts. The data acquisition system functions off a 10-volt supply of direct current.

3.6 PROCEDURE.

Figure 3-4 shows the pullout shear box just before conducting a dynamic interface test. The procedure required to set up a dynamic interface test is described as follows:

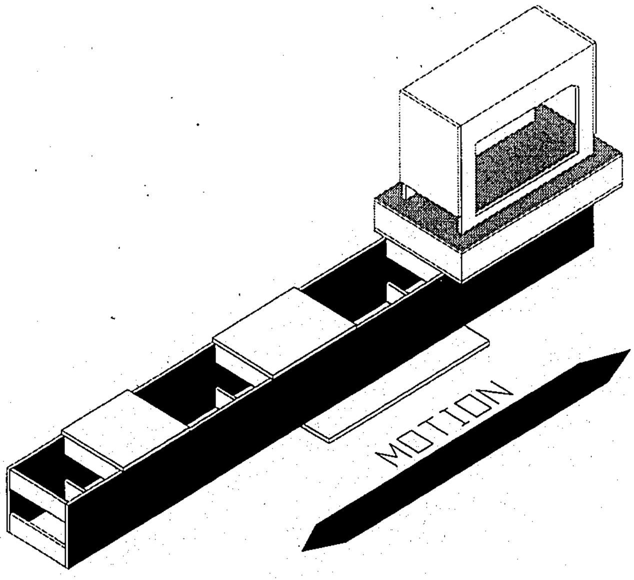
1. Remove the front side plate, top plate, glass window, and all of the air bags from the dynamic pullout shear box.
2. Position the reinforcement in the dynamic pullout shear box.
3. Install the front side plate.

4. Place the glass window on top of the reinforcing inclusion.
5. Install the side mounted air bag spacer assemblies.
6. Check to ensure that the inclusion is centered inside of the dynamic pullout shear box and that it is free to transverse in the long direction inside the box.
7. Install the side-mounted air bags assemblies and inflate the bags to just maintain the rectangular shape provided by the air bag frames with no indentations.
8. Take a volume measurement of the dynamic pullout shear box.
9. Weigh the soil and the container.
10. Place the first two-inch thick lift of soil and tamp 25 times.
11. Check to ensure that the air bags are maintaining their shape, inflating as necessary.
12. Place one additional two-inch thick lift of soil and tamp 25 times.
13. Repeat steps 5 and 6 until the soil fills the pullout shear box to the desired elevation.
14. Finish the soil surface so that it is smooth and flat.
15. Reweigh the soil and container.
16. Take another volume measurement of the dynamic pullout shear box.
17. Install the top air bag assembly.
18. Install the top plate and torque mounting screws accordingly.
19. Pressurize the air bags to the desired confining pressure.
20. Adjust the frequency and amplitude of vibration on the shake table.
21. Inspect the data acquisition system and record all values.
22. Set the displacement rate on the pullout motor.

23. Take pullout load and inclusion displacement readings at regular intervals and periodically monitor the instruments to be sure that the boundary conditions are maintained.

3.7 SUMMARY OF EQUIPMENT AND TEST PROCEDURES.

This chapter discusses the design of a dynamic interface test apparatus and its individual components. The components comprising the dynamic interface test apparatus allow variables to be controlled and implement proper boundary conditions. Some of the individual components can be readily purchased as "off-the-shelf" items, but most of the components were designed and fabricated "in house". Material selection was critical to the successful operation of the equipment. Reducing the complexities of data analyses was possible by applying uniform confining stresses and maintaining constant loaded areas. These were identified as fundamental concerns.



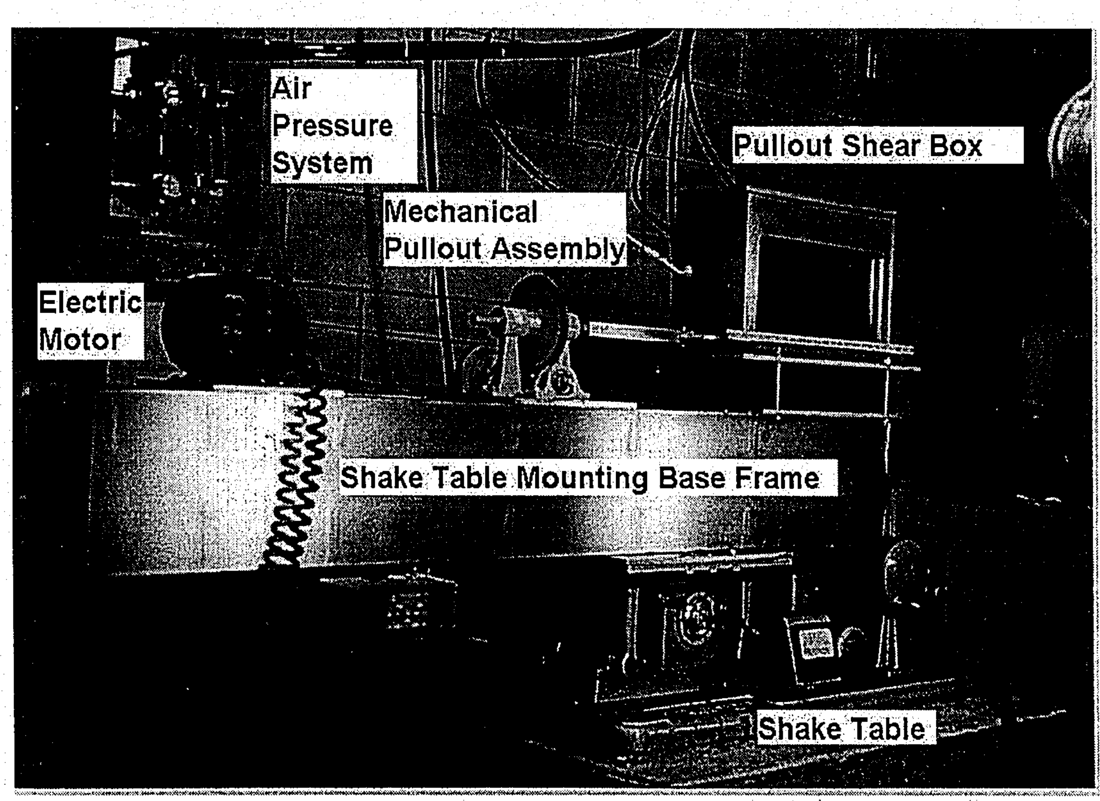


FIGURE 3-1

DYNAMIC INTERFACE TEST APPARATUS

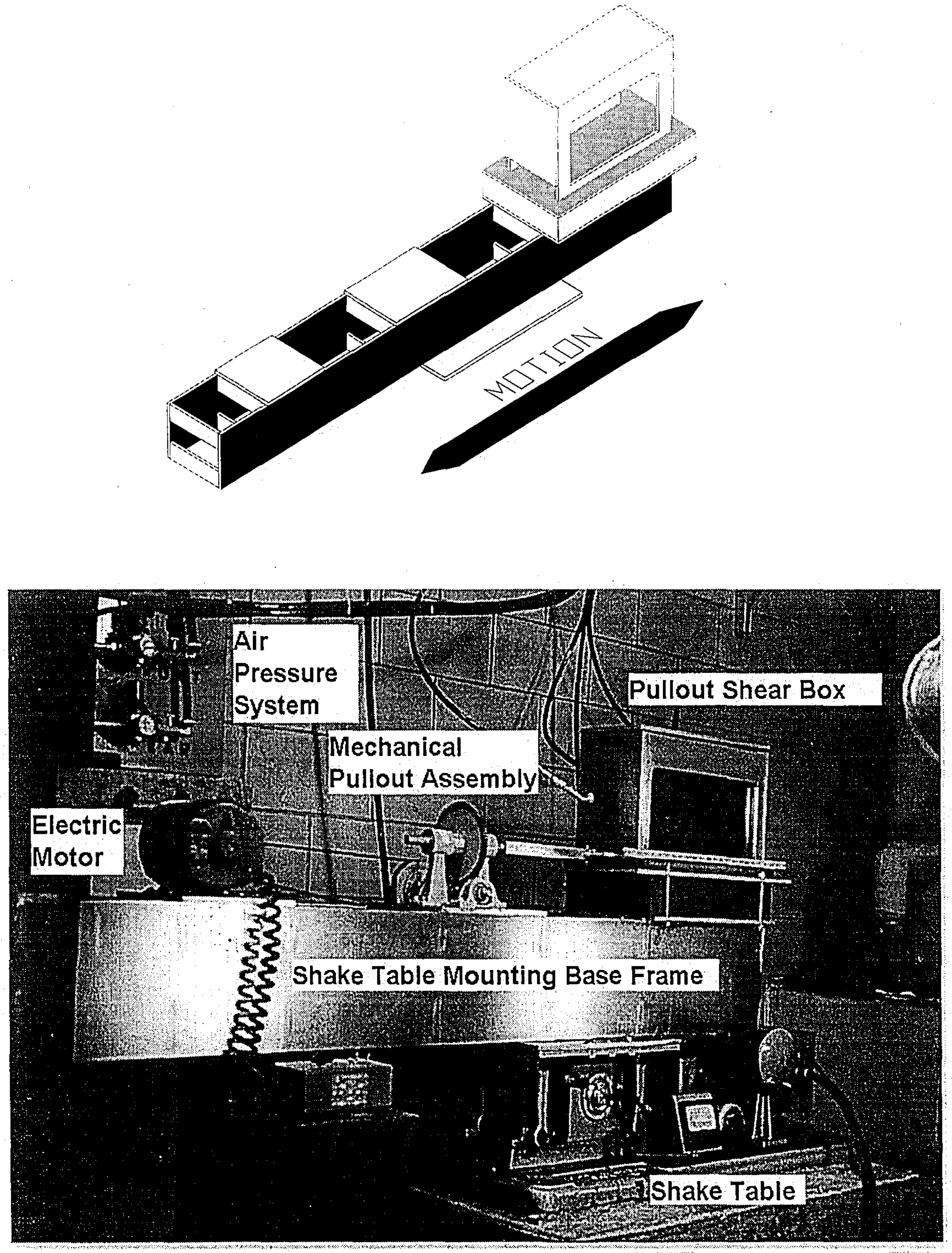


FIGURE 3-1

DYNAMIC INTERFACE TEST APPARATUS

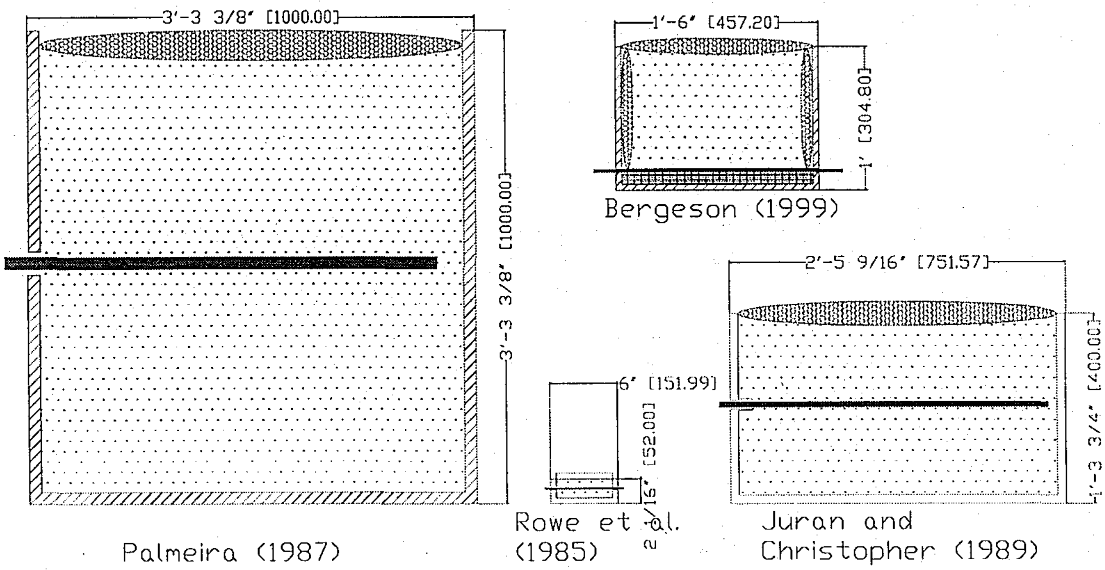
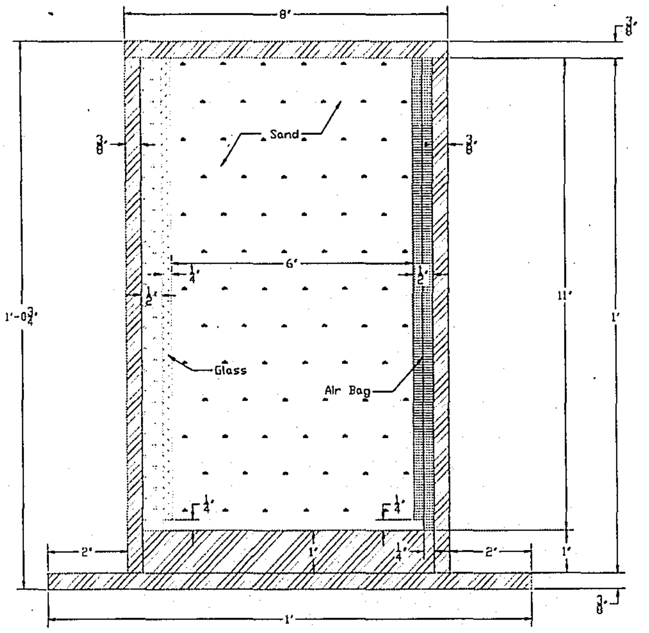


FIGURE 3-2

CONVENTIONAL PULLOUT BOXES & THE PULLOUT SHEAR BOX



End View (OPEN)

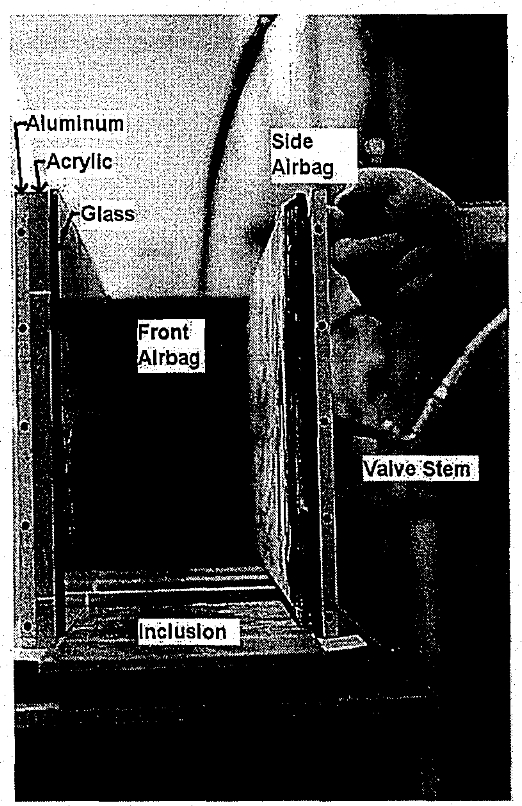
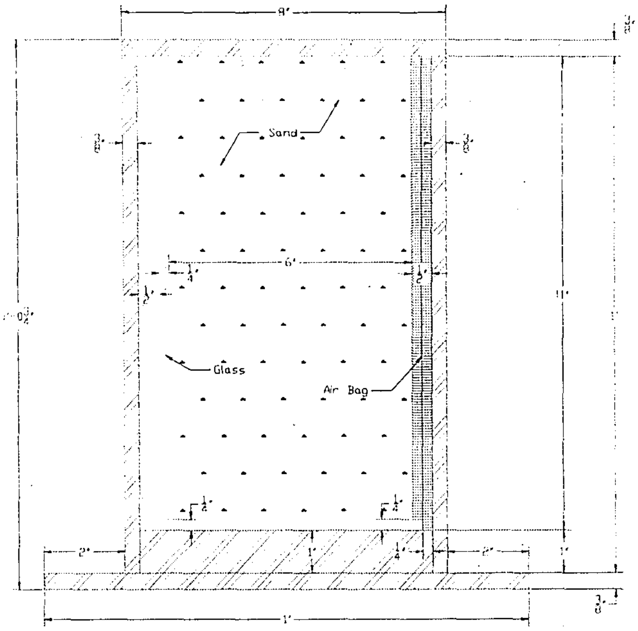


FIGURE 3-3

INTERNAL COMPONENTS OF THE PULLOUT SHEAR BOX



End View (OPEN)

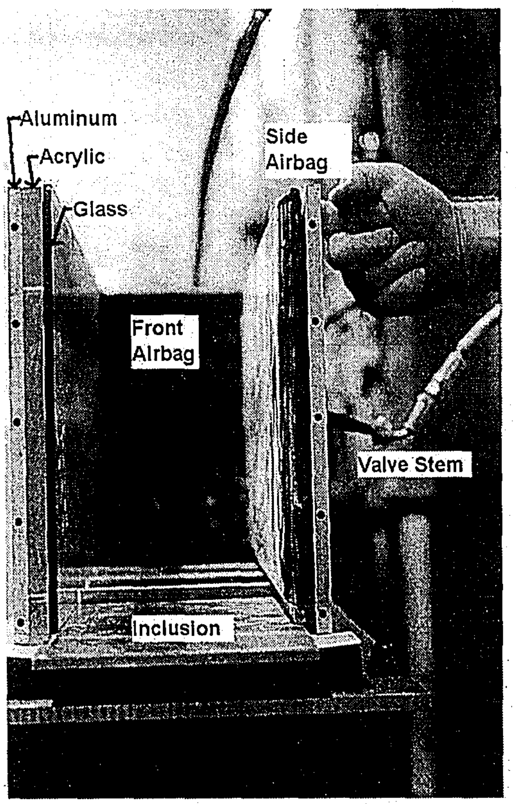
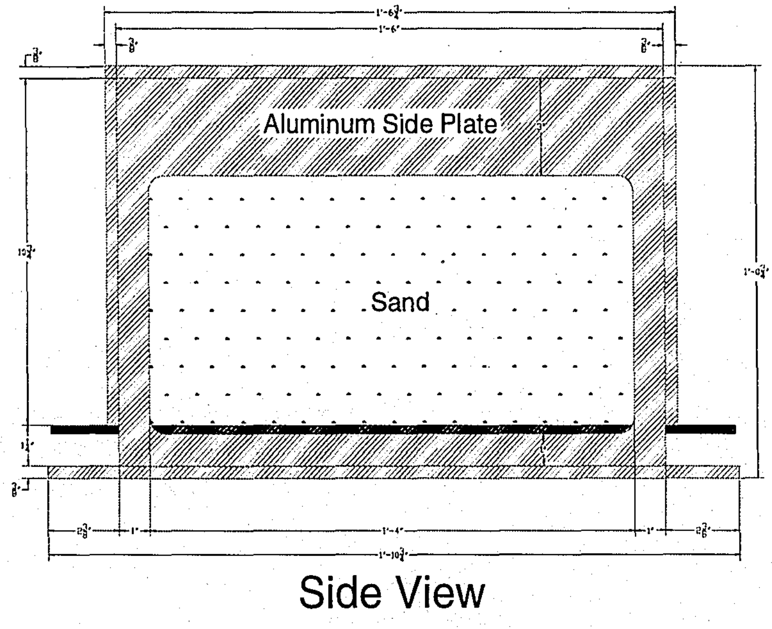


FIGURE 3-3

INTERNAL COMPONENTS OF THE PULLOUT SHEAR BOX



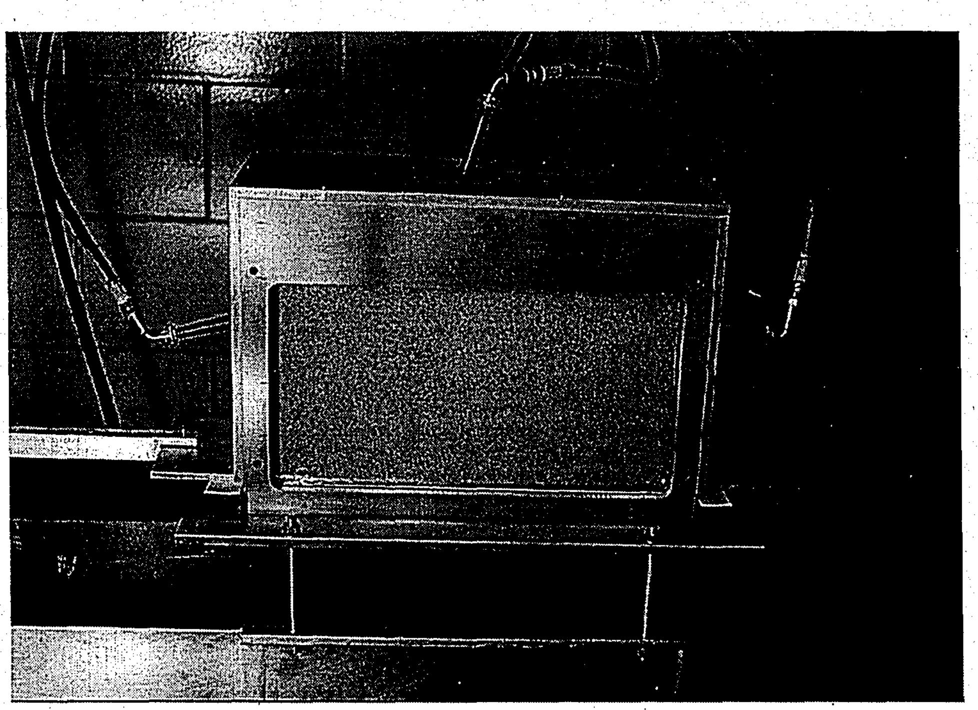


FIGURE 3-4

SIDE VIEW OF THE PULLOUT-SHEAR BOX

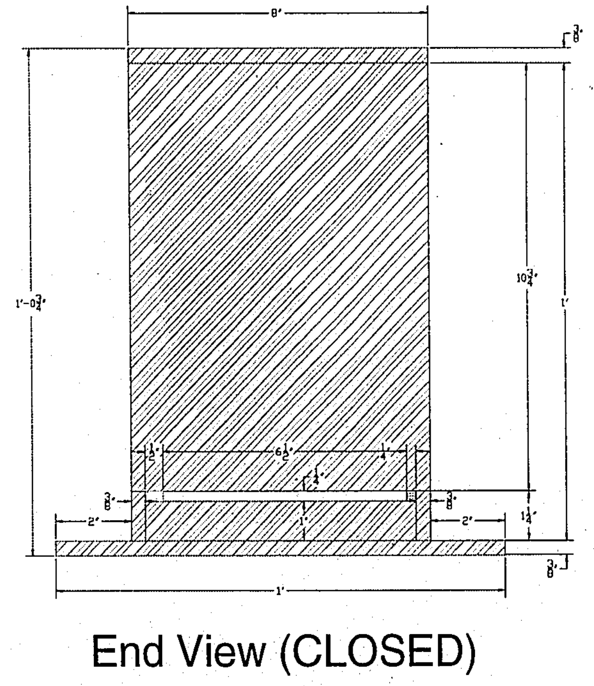


FIGURE 3-5

CLOSED END VIEW OF THE PULLOUT-SHEAR BOX

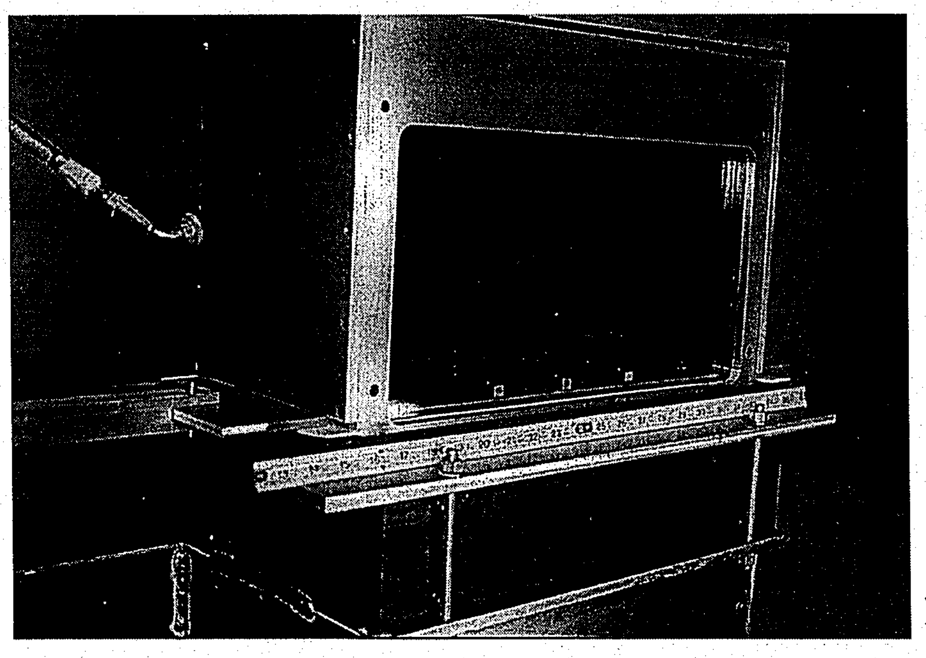


FIGURE 3-6

VALVE STEM HOLE

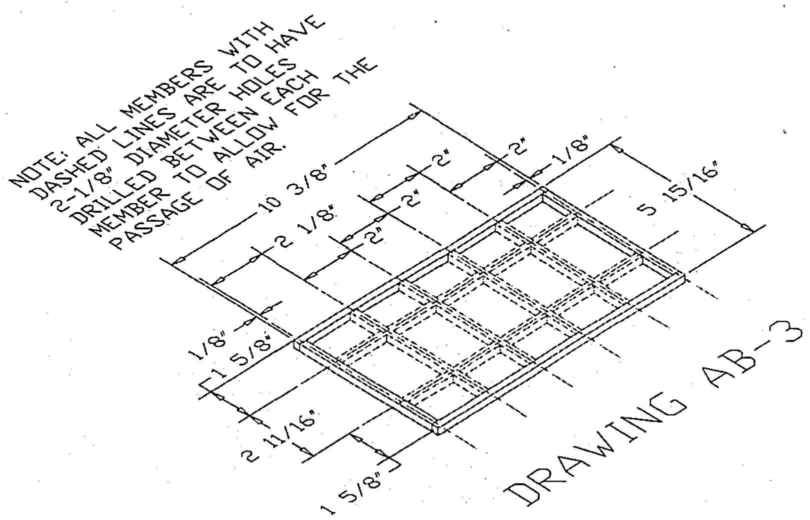


FIGURE 3-7

AIR BAG FRAME

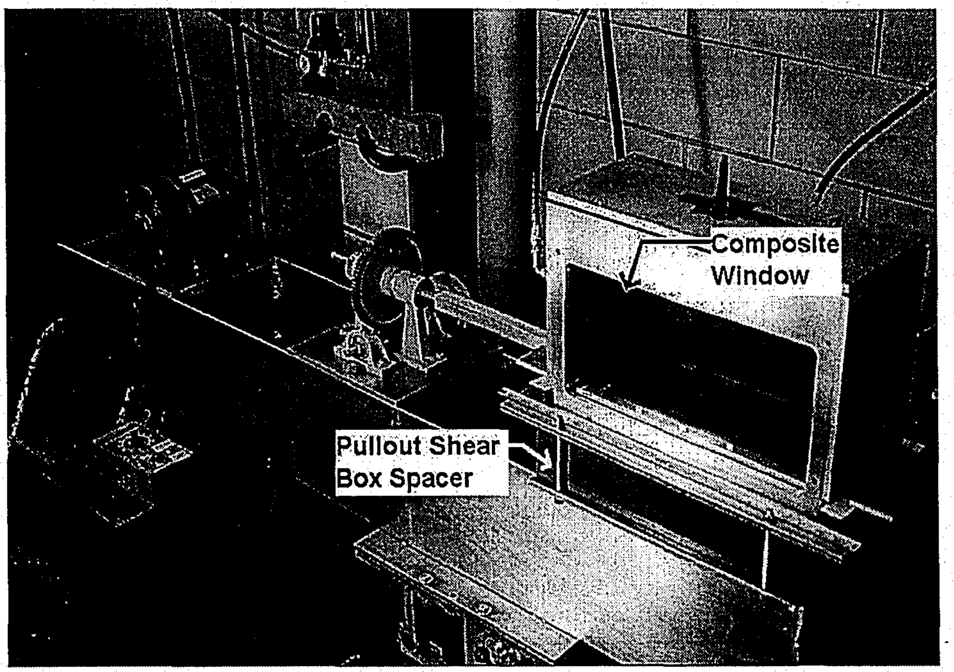


FIGURE 3-8

COMPOSITE WINDOW AND PULLOUT SHEAR BOX SPACER

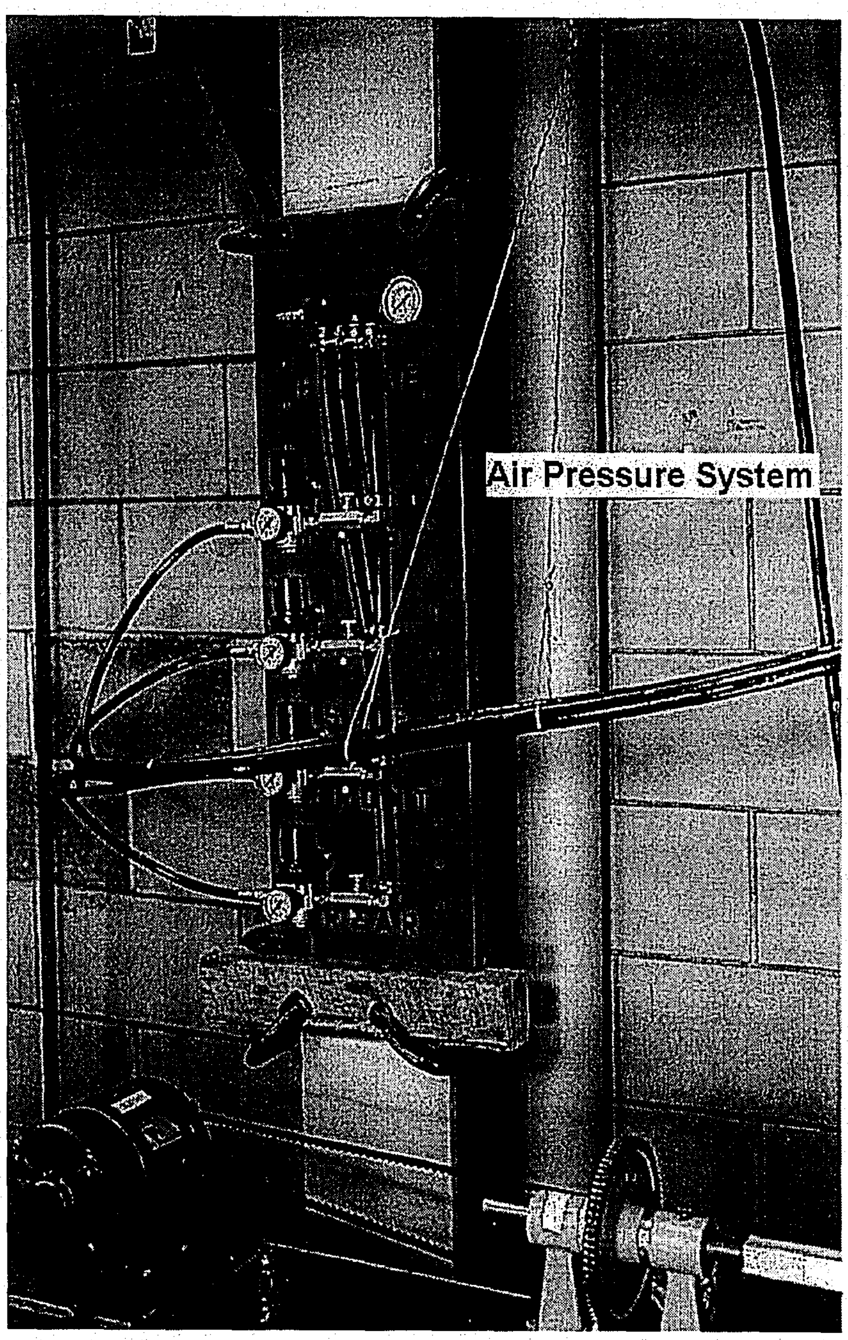


FIGURE 3-9

AIR PRESSURE SYSTEM

CHAPTER 4

4 EQUIPMENT ASSEMBLY AND RESULTS FROM ALL OF THE TESTS.

The equipment used to evaluate the dynamic interface properties between reinforcing inclusions and sand were integrated from the designed-fabricated and purchased items. The, pertinent construction and assembly details are presented in this chapter. After fabricating all of the components, performance tests were conducted to determine if this equipment functioned properly. The performance tests assured that the individual components were adequate before assembling them into the dynamic interface test apparatus. Once the components were tested and then assembled, two full-scale interface tests were conducted with the dynamic interface test apparatus to evaluate the overall design and operating performance of the assembled unit. Pullout response data was not collected during these full-scale tests due to a lack of instrumentation at the current time. Instrumentation and interface testing will commence as part of future research to be completed by others.

4.1 TEST EQUIPMENT FABRICATION AND ASSEMBLY.

Many of the individual components described in this thesis are experimental. Explanations of the construction process illustrate their effectiveness. The construction process included the major fabrication and assembly events. Most of the problems encountered during the construction process were associated with achieving specified tolerances; therefore, tolerance problems are discussed separately and in more detail. The fabrication and assembly processes for a few of the major components are also described.

Revisions to the design are described in the order that they occurred. Component tests are highlighted in this section because these tests identify when revisions or modifications were necessary. Furthermore, these tests are coupled with the construction process; nonetheless, the performance tests are more fully explained in Section 4.2.

4.1.1 TOLERANCES.

Close tolerances are necessary so that all of the equipment parts are precisely aligned. Slop or play in any of the components will result in poor performance of the device. The results obtained from the dynamic interface test apparatus are improved by eliminating any loose fitting parts.

In order to improve the results from the test apparatus, it was necessary to consider the capability of both the machinery and the operator in the fabrication shop with respect to tolerances. Before materials are cut and ordered to size, the designer always confirms the fabrication tolerances. Another problem with tolerances is compensating for positive tolerances and negative tolerances. In many situations of tolerance, it is preferable to produce a larger part than required. In tight fits the reverse may be true. However, many tolerance specifications are plus or minus a number of distance units. As a result, the part may be slightly too big, or it may be slightly too small.

With very tight fitting parts, the construction of the equipment may be problematic. For example, consider the six-sided, rigid shear box that is bolted together. A very tight fitting sheet of glass is placed inside the box. Cutting sheets of glass within 1/16th or even

1/32nd of an inch may result in a sheet of glass extending beyond the boundaries of the rigid box. Oversized 1/16th of in inch, the glass prevents the pullout shear box from being assembled. It is difficult to find glasscutters who can meet the precise tolerances.

For each material encountered, the designer must ascertain the tolerances, which can be obtained before submitting the final design. Sometimes, it may be feasible to implement shims or other components that allow the equipment to be assembled properly. The designer must be prepared to find solutions in case the tolerances are not met.

The issues of tolerances apply to almost every component used in the dynamic interface test apparatus. Tolerance problems affect the pullout shear box and its interior components because of the precise alignment required to evaluate interface behavior. The pullout shear box and internal components consist of the composite window, airbags, aluminum sidewalls, reinforcing inclusions, and friction liner. Furthermore, the locations and dimensions of the slots on the front and rear face of the pullout shear box are affected by tolerance problems. The inclusion must essentially fit the slot without contacting any part, but still prevent soil loss. .

4.1.2 CONSTRUCTION PROCESS.

The use of dissimilar materials resulted in some problems encountered during fabrication, while other problems stem from experimental designs that have to be tested, evaluated, and often revised. Materials often produce difficulty because the assumed behavior of the material may not be the same as the actual behavior of the material. Experimental designs that perform specific functions usually have to be evaluated by performance tests. Sometimes, the design needs to be revised, or the fabrication process needs to be modified before the final product can be successfully developed.

Slight problems occurred initially while estimating the outer dimensions of the airbags because the materials are unfamiliar and the designs are unique. Small tolerances are required for the airbags because the bags (contained in the pullout shear box) must fit firmly into position. The airbags dimensions are controlled by the inside size of the pullout shear box. Furthermore, the bags are designed with supporting frames inside the bags. Exterior flexible membranes surround these internal frames. To properly size the membranes, cutout patterns are used. These patterns were placed over the membrane, which was then trimmed to the required shape and size. The membrane was folded around the internal frames with overlapping the edges of the pattern cutout and glued to one another. The glue is a cold vulcanizing compound that prevents air from leaking out of the folded seams. Finally, the membrane requires additional folding to conform to the inside of the pullout shear box.

As a result of the close-fitting tolerances and the unfamiliarity with the airbag materials, the internal frames were incorrectly sized in the original design. The original fit was overly snug, and two of the airbags simply did not fit into place. Therefore, the frames had to be trimmed and fused back together with chemical adhesive. New membranes were then placed over the modified frames. It was also discovered that when the surface of the membranes are clean, they tended to stick to each other, which hindered placement of the bags. A powder composed of chalk dust was applied to the surface of the membrane to alleviate this problem.

Another problem is attributable to interfacing materials that are different in hardness. The surface of aluminum scars very easy while in contact from common metal machining bits. In fact, even small metal shavings are easily embedded into the aluminum plates and mar the softer aluminum surfaces. Furthermore, these defects in the aluminum that come into contact with any type of softer, brittle materials such as glass may result in splintering of the softer, brittle material. These splinters abrade the softer materials, such as plastic and rubber surfaces.

4.2 PERFORMANCE TEST RESULTS.

Performance tests are used to evaluate the individual components. The tests are devised to determine whether or not the components are functioning properly. Many of the tests consist of simulating an operation that will be required by the component in the dynamic interface test apparatus.

The first performance test conducted involved building a full-scale model of the pullout shear box to scrutinize the prototype design. The full-scale model is shown in Figure 4-1. An inexpensive prototype was constructed using plywood. Testing the model ensured that there were no fundamental design flaws in the final design submitted to the fabrication shop. After assembling the full-scale model, various components were examined. Examination of the side window indicates the degree to which visual observations might be obstructed. Slot configurations were evaluated using flat sheets to simulate inclusions. This assured that the size of the pullout shear box and the test scale are appropriate.

The next series of performance tests were conducted on the air pressure system. The air pressure bags maintain predefined shapes to ensure application of uniform confining pressures to the soil. As it turned out, the 1/32nd inch thick rubber membrane could not be folded as expected over the inner frames. Two of the air bags require slightly smaller frames because the folds in the membrane are thicker than expected. To correct this problem, the front and rear air pressure bags were removed and their frames were stripped of their membranes. The frames were then trimmed and fused back together again. The newly assembled frames were then covered with new membranes.

Once the bags were fit into place, they were checked for leakage by spraying the surface with mild soapy water. Leaks were easily detected by bubbles located near the defect. In the original construction method, bubbles detected leaks along the seams in the folded patterns of the exterior membranes. In order to correct this problem, additional cold vulcanizing compound was applied. With the new construction technique, the bags are virtually free from leaks in the folded seams.

Performance tests of the air pressure system were also made. The air pressure system is shown in Figure 3-9. The house air pressure supply connects to the manifold with a pressure gauge, which in turn is connected to the control valves, regulators (with gauges), and terminates at the pressure bags. Hoses, elbows, and adapters were used for the system. Systematically, the pieces are blocked off, pressurized, and checked for leaks. Initially there are leaks detected between the hose and brass fittings that connected the manifold to the control valves. Hose clamps were installed to correct this problem.

The inclusion was tested for fit inside the pullout shear box. Glass fragments broke off the composite window as the inclusion moved underneath. The defect on the inclusion resulted in splintering of the glass window, which was corrected by smoothing the inclusion with sandpaper.

4.3 FULL SCALE INTERFACE TEST RESULTS.

Two full-scale interface tests were conducted with the dynamic interface test apparatus in order to demonstrate its potential for isolating test variables and imposing appropriate boundary conditions. Both tests were conducted under identically, except that one was performed under static conditions while the other was performed under dynamic conditions at a frequency of 5 cps and displacement amplitude of 0.05 inches.

In both tests, an ideal aluminum inclusion with three cross ribs is placed on the friction liner. The side airbag and the glass portion of the composite window are placed on their respective edges of the inclusion. The front and rear airbags were then placed. The inclusion was pulled in the forward and backward directions to ensure that it was travelling freely through the slots, across the friction liner, and beneath the composite window and airbags. Next, rounded silica sand was placed in the pullout shear box, tamped, and vibrated to a high density. Once the sand was compacted, the upper air bag was placed and all of the pressure bags were adjusted to impart 10 pounds per square inch of confining pressure to the specimen. The effect of confining pressure on the sand was observed through the composite window. Next, the pullout rate of the inclusion from the box was set at 0.05 inches per minute. The inclusion was pulled out to a sufficient displacement to ensure peak pullout resistance was achieved.

The completion of the full-scale, non-instrumented tests signify an end to the design and construction phase of the dynamic interface testing apparatus. Future research by others will be conducted to examine the effects of test variables and boundary conditions on dynamic interface behavior using instrumented full-scale tests.

4.4 SUMMARY OF EQUIPMENT FABRICATION AND TEST RESLUTS

The fabrication of highly specialized equipment components used in this research presented problems relating to tolerances, unfamiliar materials and new experimental design. The problems with tolerances were the most difficult to overcome. The designer must always be aware of the tolerances that can be obtained for the construction material, fabrication equipment, and shop personnel. Another problem regarding tolerances concerns dimensioning the component parts.

Both performance tests and the full-scale tests indicate that the dynamic interface test apparatus functions properly, and will be an invaluable too for evaluating interface behavior between reinforcing inclusions and sand under dynamic and static loading conditions. Performance tests assured that the individual components function as intended. The full-scale test demonstrated that the dynamic interface test apparatus was capable of imposing appropiate boundary conditions and isolating test variables.

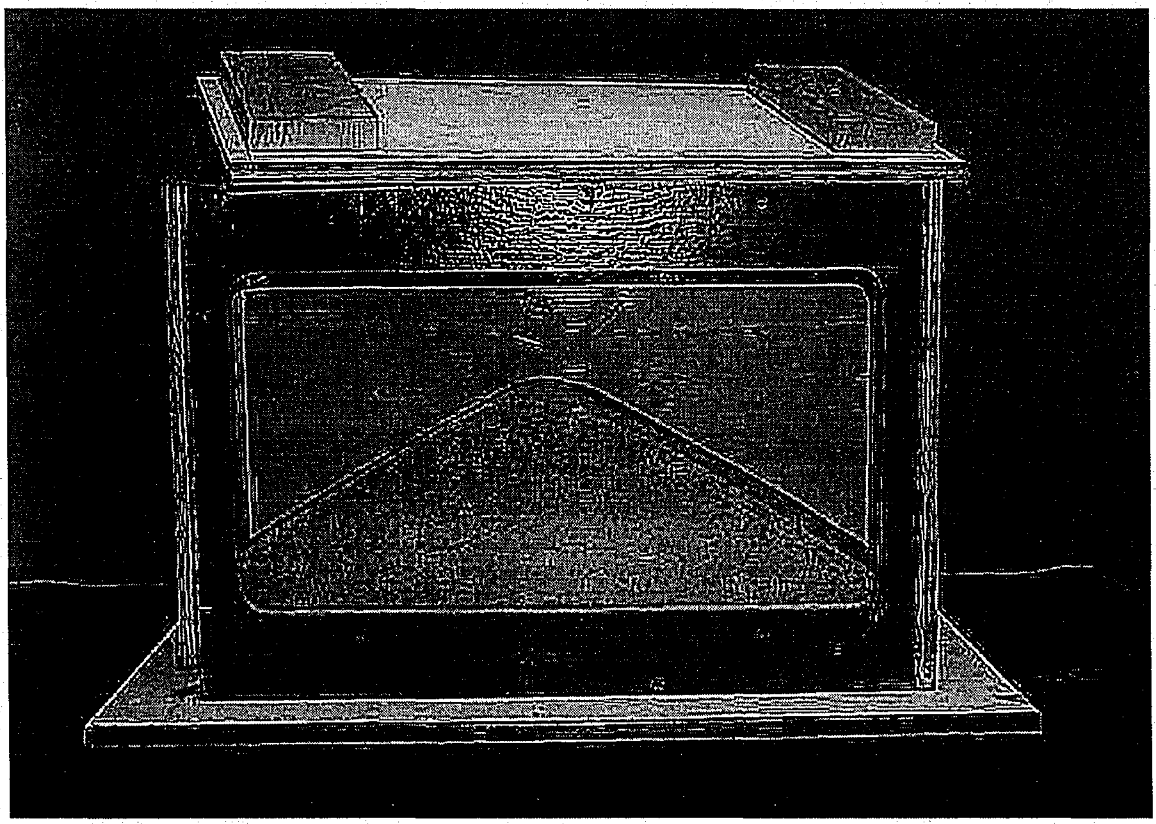


FIGURE 4-1

PROTOTYPE

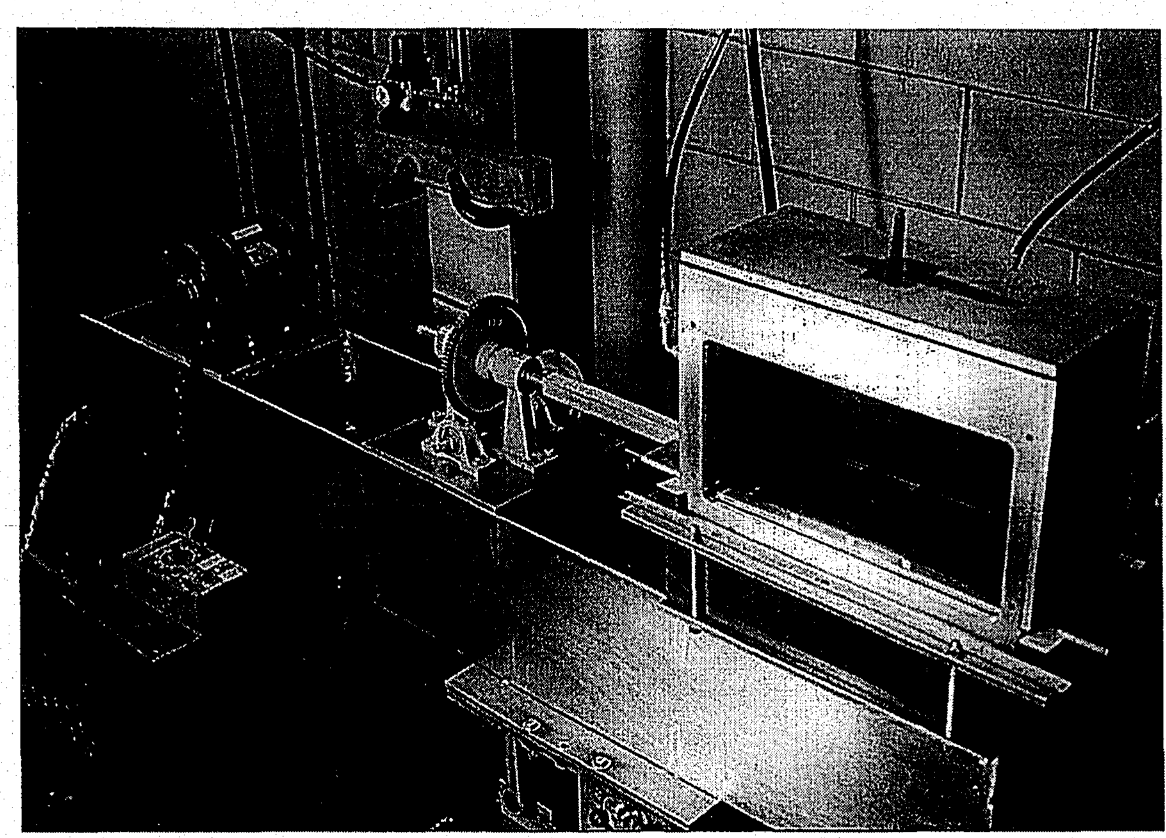


FIGURE 4-2

DYNAMIC INTERFACE TESTING APPARATUS

CHAPTER 5

5 RESEARCH SUMMARIES AND FINAL REMARKS.

The scope of this thesis completes the first phase of a larger research program to study the dynamic interface properties between reinforcing inclusions and sand. This project completes the first phase, the design and construction of the dynamic interface testing apparatus. The work completed and described in this thesis is summarized in this chapter. After summarizing the research, final remarks are presented. The final remarks consist of conclusions and future recommendations.

5.1 EQUIPMENT SUMMARIES.

The dynamic interface test apparatus was designed to have many integrated components, which allow various parameters affecting the pullout behavior of inclusions in soil to be studied. The system allows various conditions, such as confining pressure, pullout speed, frequency of vibration, amplitude of vibration, rib height to rib spacing ratio, static-dynamic loading, and particle grain size effects to be studied. Individual components of the dynamic interface test apparatus were built from various types of materials. Some of these materials were dissimilar, which led to experimental designs, revisions and/or modifications from the original prototype. This required testing of the individual components before the equipment was assembled into a single multi-functional testing apparatus. Few problems were encountered with assembling the devises because the design process made diligent use of computer-generated drawings and careful auditing of all the dimensions. Nonetheless, the development of the apparatus revealed issues concerning the design, such as tolerances, material performance, and fabrication difficulties. Problems with tolerance were the most troublesome; while experimental designs and material unfamiliarity resulted in problems that are more difficult to correct. Once all of the equipment problems were overcome, the dynamic interface test apparatus was tested and shown to perform adequately for subsequent research phases. This project completes the design and construction phase of the dynamic interface test apparatus.

5.2 TEST SUMMARIES.

Two types of tests were conducted in this research, performance tests and full-scale interface tests. Performance tests were conducted to evaluate individual equipment components ensure they functioned as intended. The full-scale tests demonstrated that all of the components in the fully assembled dynamic interface test apparatus were operational and that the design-fabrication phase was successful.

The first performance test consisted of building an inexpensive full-scale model of the pullout shear box. This ensured that there were no fundamental design flaws in the final design. Performance tests were conducted on the air pressure system including the inflatable pressure bags. These showed deficiencies in the bag construction causing leaks along the membrane seams, a poor fold pattern that did not provide for a tight fit with the pullout shear box, and the presence of leaks in the air pressure system and connecting hoses. The performance test for the inclusion show that even slight defects in the aluminum surface causes the glass riding on the edge to splinter and leave behind glass fragments. The tests also showed that the glass portion of the composite window and the side airbag rides along the outer edges of the inclusion do not interfere with the pullout of the inclusion.

The full-scale interface tests established that the dynamic interface tests apparatus is functioning correctly and that the components are able to isolate test variables and impose appropriate boundary conditions. The boundary conditions include confining pressure, pullout speed, frequency of vibration, and amplitude of vibration. All of these boundary conditions may be easily altered. Isolated test variables include rib height to rib spacing ratio, static-dynamic loading, and soil type.

5.3 RESEARCH SUMMARY.

Researchers have recently studied load transfer from soil to inclusions under static conditions, cyclic pullout response of inclusions embedded in soil, and the dynamic interface behavior between two geosynthetics. It is understood that load transfer is complicated and depends on many different parameters. Due to a lack of fundamental understanding of the pullout behavior under dynamic conditions, designs are typically overly conservative and unnecessarily expensive. In order to fully understand the interface behavior between the soil and the inclusion, a test devise needs to allow the various parameters to be isolated. The scope of this project included design and construction of a highly specialized test apparatus that incorporates some concepts from existing devices, and incorporates many new features. The apparatus is composed many components making the machine capable of multi-functional operations. Fundamental concerns were identified early in the program and goals were set regarding the performance of the equipment in the preliminary design phases. A distinction was identified between fabricated equipment and equipment that is acquired as "off-the-shelf" items. Equipment components were chosen to isolate the variables affecting interface behavior and to provide proper boundary conditions. These components were integrated into the dynamic interface test apparatus. Much of the fabricated equipment was constructed from materials that generally are unfamiliar and dissimilar in their physical properties.

Performance tests demonstrated that the components function as intended, although many modifications were needed. After completing all of the performance tests, two full-scale interface tests were conducted. The full-scale tests were conducted to evaluate the behavior of the fully assembled dynamic interface test apparatus. These full-scale tests were conducted under identical conditions, except that one was performed under dynamic test conditions while the other was performed as a static test. Results from all of the performance tests and both of the full-scale interface tests indicate that the new apparatus is adequate for studying the dynamic interface response between reinforcing inclusions and sand. The side window allows visual inspection of the particle displacement at the interface, which will allow better understanding of the mechanical interaction between the soil and inclusion under dynamic conditions.

5.4 RESEARCH CONCLUSIONS.

Concluding remarks are made here, addressing critical judgements made during this research project. Conclusions regarding problems with tolerances, unfamiliar materials, and experimental design are presented. Conclusions are also drawn on future research into dynamic interface testing between reinforcing inclusions and sand.

Becoming aware of the limitations of the fabrication equipment, shop personnel, and the material to be fabricated, can reduce problems associated with tolerances. The precision of fabrication equipment varies considerably. The skills of the fabrication equipment operators also vary with experience. The material may have unique characteristics that are only understood after experimentation. Development of mini-components (such as shims) to compensate for larger than desirable tolerances are often required. A phased construction program help in dealing with these issues in experimental device development. Phased construction allows the designer to evaluate the equipment components and make subsequent modifications to the individual components if the tolerances are not met.

Unfamiliarity with materials and equipment, however, does not mean that adequate designs are not practicable. Adequate design requires research, contemplating what is known, asking many questions, extrapolating knowledge to the unfamiliar, and experimenting as necessary.

Experimental designs can achieve the desired performance with careful planning. Computer programs such as SAP2000 and AutoCAD allow design parameters to be carefully studied. However, experimental designs also require development and testing of models and prototypes.

5.5 FUTURE RECOMMENDATIONS.

This project has set the foundation for new research into the interface properties between reinforcing inclusions and sand under dynamic conditions. The next phase of this research is to test boundary conditions and other test variables. Since the boundary conditions and variables can be easily altered, all of the assumptions must be identified and recorded before analyzing the interface test results.

There are several issues that need to be studied in future interface-testing program. The effects of dynamic excitation on interface behavior (frequency and amplitude), ideal rib height to rib spacing, and isotropic versus anisotropic confining pressures need to be studied in order to provide better information to earth system designers. Digital imaging equipment should be used to capture the deformation within the soil to assess if the failure mechanism under dynamic conditions is fundamentally different then under static conditions.

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VITA

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